DEVELOPMENT OF EMPIRICAL MODELS FOR PREDICTING THE EFFECTS OF VISCOUS INSTABILITIES IN IMPROVED OIL RECOVERY BY WATERFLOODING

[PART OF ENERGY, MINES AND RESOURCES COST SHARED ENERGY CONVERSION PROGRAM AND PART OF THE PROGRAM OF THE FEDERAL PANEL ON ENERGY R&D (PERD)]

FINAL REPORT

by:

B.B. MAINI, H.K. SARMA, J. GOLDMAN AND R.W. PURVES
Petroleum Recovery Institute
3512-33rd Street N.W.
Calgary, Alberta T2L 2A6

Work on the project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy, Mines and Resources Canada.

DSS FILE No. 006SQ.23440-9-9260
DSS CONTRACT SERIAL No. 23440-9-9260/01-SQ
CANMET SCIENTIFIC AUTHORITY: Dr. K. Jha

MICROMEDIA

98pp

March 1992

TABLE OF CONTENTS

EXECUTIVE SUMMARY iii

SOMMAIRE EXECUTIF iv

INTRODUCTION 1

LITERATURE REVIEW 4

STUDIES BASED ON MICROSCOPIC APPROACH 4
STUDIES BASED ON MICROSCOPIC APPROACH 9
EXPERIMENTAL STUDIES OF VISCOUS FINGERING 10
RELEVANT DIMENSIONLESS NUMBERS 12

OBJECTIVES 14

EQUIPMENT, MATERIALS AND METHODS 15

EQUIPMENT 15
Rig #1 15
Rig #2 16

MATERIALS 16
Porous Media 16
Fluids 16

RESULTS AND DISCUSSION 20

A. DISPLACEMENTS IN TUBULAR GEOMETRY 20
EFFECT OF GEOMETRIC FACTORS ON PSEUDO-RELATIVE PERMEABILITY 21

EFFECT OF GEOMETRIC FACTORS ON BREAKTHROUGH RECOVERY 22

EFFECT OF GEOMETRIC FACTORS ON RECOVERY AT 10 PORE VOLUMES INJECTED 23

B. DISPLACEMENTS IN RECTANGULAR GEOMETRY WITH FLOW VISUALIZATION 23
Effect of Displacement Rate on Oil Recovery 24
Effect of Viscosity Ratio on Oil Recovery 24
Effect of the Initial Wetting Condition on Oil Recovery 25
Effect of Gravity 25

Effect of Capillary Number 25
Pseudo-Relative Permeabilities 26
Effect of Instability Number on Breakthrough Recovery 27

CONCLUSIONS 29

NOMENCLATURE 31

REFERENCES 33

EXECUTIVE SUMMARY

Improved oil recovery by water flooding often involves displacing a more viscous fluid (oil) with a less viscous fluid (water). Because of the adverse viscosity ratio involved, such displacements are impaired by viscous fingering and result in very poor recoveries. The conditions which lead to viscous fingering are well documented (Pavone, 1989; Peters and Flock, 1979, Chuoke et al. 1959). Although it is currently possible to roughly predict whether or not a field displacement is likely to be unstable, it is nearly impossible to predict the recovery performance of unstable displacements. Although viscous fingering has been studied by many, the displacement data reported in the literature are not complete enough for developing an empirical model for predicting the performance of unstable floods. In most cases the displacements were terminated soon after water breakthrough. Often the systems used were inadequately characterized.

The objective of this work was to investigate the behaviour of unstable displacements and develop ways of modelling the recovery performance of such displacements. A review of the available literature on viscous fingering in immiscible displacements was carried out and the scaling criteria reported in the literature for onset of viscous fingering were examined.

More than 30 oil displacement tests were carried out to examine the effects of three important parameters -- the L/D ratio in linear systems; the viscosity ratio; and the flood velocity. The results showed that the displacement performance was not affected by the value of the geometric ratio. However, the flood performance was affected significantly by the values of the viscosity ratio and the flood velocity.

It was found that the oil recovery and the pressure drop history of these unstable displacements could be satisfactorily matched with the conventional Buckley-Leverett frontal advance theory by using modified relative permeability curves. Such pseudo-relative permeability curves were determined for all experimental displacements. These pseudo-relative permeability curves were found to be relatively independent of the L/D ratio but varied with the viscosity ratio and the flood velocity. The end-point water relative permeability increased with increasing displacement rate.

Contrary to what would be expected from the current instability theory, both the breakthrough oil recovery and the ultimate oil recovery increased with increasing displacement rate in very adverse viscosity ratio systems. However, the effect of viscosity ratio was consistent with the current instability theory in that the breakthrough recovery and the ultimate recovery decreased with increasing viscosity ratio.

It is suggested that the wettability number proposed by Peters and Flock should not be assumed to be constant for a particular rock-fluid system but made a function of the displacement rate.

SOMMAIRE EXECUTIF

La récupération accrue d'huile par déplacement d'eau implique souvent le déplacement d'un liquide visqueux (huile) par un liquide de moindre viscosité (eau). La qualité de ces déplacements est amoindrie par le rapport de viscosité peu favorable. Les conditions qui mènent à cette digitation visqueuse sont citées à maintes reprises par des auteurs tels que (Pavone, 1989; Peters et Flock, 1979; Chuoke et al. 1959). Même s'il est possible de prédire la stabilité d'un déplacement, les données rapportées dans la littérature ne sont pas assez complètes pour permettre le développement d'un modèle empirique qui pourrait prédire le comportement de déplacements instables. Pour la plupart, les déplacements sont arrêtés aussitôt que l'eau perce. Souvent, les modèles utilisés n'étaient pas suffisamment bien définis.

Ce travail avait pour objectif d'investiguer le comportement de déplacements instables et aussi, de trouver une façon de modeler ces déplacements. Ainsi, nous initiâment une revue de la littérature sur les doigts de viscosité pour des déplacements immiscibles. De plus, on examina les critères dominant l'initiation de la formation de ces doigts visqueux.

Pour ce faire, plus de 30 déplacements furent effectués pour que l'on puisse examiner les trois paramètres suivants -- le rapport longueur/diamètre dans les systèmes linéaires; le rapport de viscosité; et finalement; la vélocité du déplacement. Les résultats démontrèrent que la qualité du déplacement n'était en rien affectée par le rapport géométrique. Cependant, la performance du déplacement fut considérablement affectée par les rapports de viscosité et de vélocité du déplacement.

Ainsi, on trouva que la récupération d'huile et la pression différentielle de ces systèmes instables pouvaient être modelées par la théorie d'avance frontale de Buckley-Leverett, et ce, en utilisant les courbes de perméabilité relative. De telles pseudo courbes de perméabilité relative furent déterminées pour chacun de ces déplacements expérimentaux. On constata que ces pseudo courbes étaient relativement indépendantes du rapport géométrique mais qu'elles variaient avec les rapports de viscosité et la vélocité du déplacement. La perméabilité relative de l'eau correspondant à la saturation résiduelle de l'huile s'est accrue lorsque le taux de déplacement a augmenté.

L'apparition de l'eau et la récupération ultime d'huile se sont accrues avec l'accroissement du taux de déplacement, et ce, même si les rapports de viscosité étaient très peu favorables. Il est à noter que ce résultat va à l'encontre de la théorie actuelle sur les déplacements instables. Cependant, l'effet de rapport de viscosité était en accord avec la théorie des déplacements instables qui prévaut en ce moment. En effet, la récupération après l'apparition de l'eau et la récupération ultime ont diminués avec l'augmentation du rapport de viscosité.

Il est suggéré que le nombre de mouillabilité proposé par Peters et Flock ne devrait pas être assumé comme une constante pour un système donné, mais bien comme une fonction du taux de déplacement.

INTRODUCTION

Secondary recovery of oil by water flooding is an efficient process provided the water advances as a stable front and sweeps the reservoir uniformly. This occurs when the oil is more mobile than the displacing water and the reservoir is not too heterogeneous. However, when the oil mobility is low, as would be the case in medium gravity and heavy oils, the displacing water has a tendency to finger through the oil and this leads to poor recovery efficiency. The factors which control this type of flow instability include the displacement velocity, oil/water viscosity ratio, relative permeability characteristics and the interfacial tension between oil and water. Our current understanding of this problem is limited to predicting the conditions under which viscous fingering is likely to occur and we are still unable to adequately describe how the fingers propagate and grow under different conditions. Consequently, it is not possible to predict oil recovery versus pore volumes injected in a waterflood affected by viscous fingering. This limits our ability to optimize the operating strategies in such cases. It is therefore desirable to develop tools for predicting the recovery behaviour of unstable displacements, i.e. displacements involving viscous fingering.

The physics of immiscible displacements in porous media involving viscous fingering is extremely complex and involves a wide variety of pore scale phenomena, including wetting, dynamic contact angles, dynamic interfacial tensions, stability of liquid films, mobilization and trapping of blobs of the non-wetting phase and heat and mass transfers across interfaces. Consequently, it is not readily amenable to theoretical analysis. Mathematical models of the growth and propagation of viscous fingers, even under idealized conditions are yet to be

developed. Therefore, it is necessary to rely on empirical methods to predict the oil recovery performance of waterfloods involving viscous fingering.

Reservoir engineers generally rely on numerical simulations of the displacement process for predicting flood performance. Most, if not all, of the available simulation models of immiscible displacements are based on the concept of relative permeability which was introduced by Muskat (1937) to extend Darcy's law to simultaneous flow of two liquids. The system of equations for describing the displacement of one liquid by another was solved analytically by Buckley and Leverett (1942) for a special case of linear displacement in which the effects of gravity and capillarity were neglected. However, the general case of a three-dimensional displacement involving gravity and capillarity can only be solved numerically. Such numerical solutions employ laboratory measured relative permeability curves to portray the effects of microscopic distribution of oil and water in the porous medium. This approach has been generally successful in history matching the performance of stable displacements. However, major modifications of the laboratory measured relative permeability curves are often needed to improve the history match. Such modifications are justified in view of the vast differences in the scales of heterogeneities between the laboratory and field displacements. It is remarkable that even though the theoretical treatment is based on the assumption of a homogeneous porous medium, adjustments in relative permeability curves are often sufficient to account for the presence of heterogeneities.

It has been reported in the literature that the concept of relative permeability can also be extended to the case of unstable displacements (Hughes and Murphy, 1987). In this situation the relative permeability becomes a lumped parameter which represents the combined effects of

the microscopic distribution of fluids and the macroscopic distribution (i.e. the size and shape of viscous fingers). This lumped parameters should be called pseudo-relative permeability to distinguish it from the true relative permeability which is an intrinsic property of the system. Unfortunately, unlike the true relative permeability, this pseudo-relative permeability is likely to vary with the physical dimensions of the system and other displacement parameters and can not be measured in the laboratory. However, it may be possible to develop empirical relationships to predict the pseudo-relative permeability from known characteristics of the reservoir and the operational parameters of the displacement.

LITERATURE REVIEW

The displacement of oil from a porous medium by injection of another immiscible fluid has been studied extensively in the literature. Most of the theoretical developments in this area are based on the application of the frontal advance theory developed by Buckley and Leverett (1942). They visualized a sharp front separating the displaced and displacing fluids. This idealized piston-like displacement may occur when the viscosity of the displacing fluid is much higher than the oil viscosity. However, when a viscous oil is being displaced by a less viscous fluid, the ideal piston-like displacement is replaced by irregular intrusion of the displacing fluid into the oil saturated regions of the porous medium. This type of intrusion was first observed by Engelberts and Klinkenberg (1951) who coined the term "viscous fingering" to describe this phenomenon. Since then, viscous fingering has been investigated in many theoretical and experimental studies and the factors that control its onset have been identified.

Most reported studies of viscous fingering have examined the phenomenon from one of the two distinct perspectives: (1) a microscopic approach in which the finger is examined as an individual entity and information regarding inception, growth and number of fingers present is extracted from the perturbation theory; and (2) a macroscopic approach in which the details of fingers are overlooked and the attention is focused on the averaged properties of the system. In the following discussion we briefly examine both approaches.

STUDIES BASED ON MICROSCOPIC APPROACH

This approach relies on the application of perturbation theory to determine the conditions

necessary for the onset of instability under idealized flow conditions. The presence or absence of viscous instabilities is inferred by determining whether a small perturbation in the interface separating the displaced and displacing fluid will grow or decay with time. In general any disturbance can be represented as a Fourier Series, of which only the least stable term would be of concern. Often, to simplify the mathematical treatment, it is necessary to linearize the displacement equations by assuming the magnitude of the disturbances to be small. Therefore, theoretically, the scaling criteria based on this approach should be applicable only to the very beginning of the fingering process.

A scaling criterion for predicting the onset of viscous fingering, based on the microscopic approach mentioned above, was developed by Chuoke et. al. (1959). They found that the capillary pressure had a suppressing effect on viscous fingering. By conducting a number of oil displacement experiments at different rates and viscosity ratios they found that the presence or absence of viscous instabilities could be correlated with a dimensionless number. According to their analysis, viscous fingering will occur at all velocities $V > V_c$, where V_c is given by:

$$\left[\frac{\mu_o}{k_o} - \frac{\mu_w}{k_w}\right] V_c + (\rho_o - \rho_w)\, g \,\mathrm{Cos}\,\theta = 0 \qquad (1)$$

provided the perturbation contains wavelengths greater than λ_c defined by:

where σ^* is the effective interfacial tension in the porous medium. It represents the product of the actual interfacial tension and a correction factor which represents the ratio of the rate of

$$\lambda_c = 2\pi \sqrt{\frac{\sigma^*}{(\frac{\mu_o}{k_o} - \frac{\mu_w}{k_w})(V - V_c)}} \qquad (2)$$

increase in interfacial area at the microscopic level to the rate of increase in macroscopic interfacial area. Since the microscopic interfacial area can be many times the macroscopic interfacial area, this correction factor is considerably larger than 1.

They also found that a particular wavelength would provide maximum instability and would dominate the fingering process. This wavelength can be related to the critical wavelength by:

$$\lambda_m = \sqrt{3}\ \lambda_c \qquad (3)$$

The theory of Chuoke et al. (1959) was extended by Peters and Flock (1981) by imposing an additional boundary condition at the walls of the porous medium: that all velocities normal to the core wall became zero at the wall. This enabled them to introduce the system dimensions into their analysis and develop a dimensionless number for quantitative prediction of the onset of instability. Their instability number for a cylindrical system is given by:

$$I_{SC} = \frac{(M-1)\ (V-V_c)\ \mu_w D^2}{c^*\ \sigma\ k_{wr}} \qquad (4)$$

where

$$V_c = \frac{k_{wr}\,(\rho_w - \rho_o)g\,\cos\theta}{\mu_w\,(M-1)} \qquad (5)$$

and

$$M = \frac{k_{wor}\,\mu_o}{k_{oiw}\,\mu_w} \qquad (6)$$

The critical value of the stability number was determined to be 13.56. According to their analysis, a displacements becomes unstable when the stability number exceeds 13.56.

The parameter c^*, called wettability number by Peters and Flock, in Equation 4 is an empirically fit parameter which represents the effect of capillarity and depends on the interfacial tension and wettability of the system. Based on their experimental results, Peters and Flock estimated c^* to be 305 for their water-wet system and 5.0 for their oil-wet system. They did not suggest a method for estimating the value of this parameter for other systems.

Bentsen (1985), using the concept of force potential rather than the velocity potential used by Peters and Flock, developed a new instability number. His approach enabled him to take into account the effect of the particular rock-fluid properties on stability. All parameters in Bentsen's instability number, with the exception of the pseudo-interfacial tension, are readily measurable. To overcome the problem of estimating the pseudo-interfacial tension, he developed a relationship between this parameter and the capillary pressure versus saturation curve (Bentsen, 1986). In a recent paper Chakrabarty and Bentsen (1991) have extended the original work of Bentsen, which was limited to the rectangular systems, to the cylindrical systems. For a cylindrical system, their stability criterion is given by:

$$I_{st} = \frac{(M-1)\,(V-V_c)\,\mu_w D^2}{\sigma_e\, k_{wor}}\left(\frac{M^{2/3}+1}{2M^{2/3}}\right) \leq 13.56 \qquad (7)$$

This stability number is proportional to the one derived by Peters and Flock, the constant of proportionality being a function of the mobility ratio.

All of the above mentioned, perturbation theory based, investigations used a description of the displacement in terms of two macroscopically distinct, single phase flow regions separated by an abrupt, macroscopic, interface. This is equivalent to assuming that the two-phase flow transition region is of a macroscopically negligible width and can be replaced by an abrupt interface. Furthermore, it is also assumed that this abrupt interface behaves much like an interface between two bulk phases so that an effective interfacial tension can be assigned to it. This is necessary to obtain a relationship between the pressures in the two phases across the interface. The validity of this effective interfacial tension concept remains questionable (Homsy, 1987)

Hagoort (1974) used an alternate and seemingly more realistic approach. He treated the stability of the one dimensional displacement in which the Buckley-Leverett front was modified by capillarity to the shape of a diffuse profile. The thickness of this frontal zone depends on the capillary number. He showed that the mobility ratio at the front, which can differ significantly from the end point mobility ratio, determines the stability.

Yortsos and Huang (1984) reported a linear stability analysis which included the two-phase flow characteristics. They showed that, in the absence of capillarity, the displacements become unconditionally unstable provided the undisturbed total mobility profile contains any

segments of decreasing mobility in the direction of flow. The presence of capillarity was shown to exert a strong stabilizing influence. In a separate paper, Huang et al. (1984) reported results of numerical solutions to their stability equations for some special cases using model equations for relative permeability and capillary pressure. It was shown that for fixed viscosity ratio and relative permeability functional forms, the minimum wavelength required for the onset of instability increases with an increase in permeability and decreases with an increase in the capillary number.

STUDIES BASED ON MICROSCOPIC APPROACH

Studies based on this approach attempt to develop empirical or semi-empirical relationship between the observed macroscopic performance of the displacement process and the independent variables of the process. The studies by van Meurs and van der Poel (1958); and Vossoughi and Seyer (1984) are good examples of this approach.

Transparent models were used by van Meurs and van der Poel to observe the development of viscous fingers during displacement of a viscous oil by water. They used a segregated flow model to derive formulae for calculating oil production and pressure drop as a function of the cumulative water injection with oil/water viscosity ratio as a parameter. The breakthrough recovery , N_{Pb}, was found to be:

$$N_{Pb} = \frac{(\sqrt{(R-1)\ B\ S_{wi}} + B)^2}{RB} \qquad (8)$$

where:

$$R = \mu_o/\mu_w$$

$$B = 1 - S_{or} - S_{wi}$$

Vossoughi and Seyer used the concept of relative flow area available to each fluid at any point in the bed instead of the relative permeability and defined a saturation dependent average viscosity characterizing the mixed zone. They derived the following relationship for breakthrough recovery.

$$N_{Pb} = \frac{R - 1}{R \ln(R)} \tag{9}$$

EXPERIMENTAL STUDIES OF VISCOUS FINGERING

A number of experimental investigations of viscous fingering, and its effect on oil recovery have been reported in the literature. van Meurs (1958), based on displacement experiments in a transparent model, reported that viscous fingering was caused by adverse viscosity ratios.

de Haan (1959) studied the effect of capillary forces in the water drive process by varying the flow rate, viscosity ratio and the wetting conditions. He found that, at low flow rates, the recovery increased with increasing flow rate but reverse was true at high flow rates. He suggested that at low flow rates the recovery was low due to the formation of immobile oil pockets. Increasing the flow rate improved recovery by decreasing the size of these pockets. However, with adverse viscosity ratio, if the flow rate was further increased, the recovery declined due to onset of viscous fingering. He also reported that the wetting condition had a

direct influence on the fingering process.

Perkins and Jonston (1969) investigated the simultaneous flow of water and oil in linear models and showed that the immiscible fingers deteriorated into a longitudinal zone of graded saturation before travelling very far in a linear, uniform, bead packed model. Gupta and Greenkorn (1973) showed that numerous incipient fingers occurred at the beginning of the flood but only a single dominant finger propagated at the later stages. They also found that a fully swept stable zone was present at the upstream end and this stable zone advanced at a slow rate. The only variable studied in this work was the flow rate and it was found that the finger tip velocity was constant at each flow rate.

Hagoort (1974) investigated the effect of displacement rate on breakthrough recovery and found that a decrease in breakthrough recovery occurred at high rates due to viscous instability.

Peters and Flock (1979) carried out displacement experiments in sand packs and developed a more advanced scaling criterion for predicting the onset of viscous fingering. They showed that viscous fingering could occur both in presence and absence of connate water saturation. Furthermore, they found that all experiments involving adverse viscosity ratio were unstable in absence of the connate water, whereas, only high rate floods were unstable in the presence of connate water.

Pavone (1989) used a moulding technique to investigate viscous fingering. He found that the breakthrough recovery and the saturation profiles calculated from shape of the solidified fingers could be correlated with two dimensionless numbers. However, his experiments were stopped at the breakthrough of the displacing phase and provide no information on post breakthrough recovery.

Peters and Khataniar (1987) and Maini and Coskuner (1988) have shown that the relative permeability calculated from unstable displacement experiments is affected by the extent of instability present. Maini and Coskuner have also shown that the overall recovery performance of unstable displacements can be described by Buckley Leverett type displacement theory, i.e. even though the basic assumptions of the frontal advance theory are not met, the resulting pressure drop and recovery history can be matched by using appropriate pseudo relative permeability characteristics. Such relative permeability curves are, undoubtedly, sensitive to the variables that control the viscous fingering. Presently, it is not known how to predict the pseudo relative permeability curves from the knowledge of the true relative permeability and the factors controlling viscous fingering.

RELEVANT DIMENSIONLESS NUMBERS

Because of the large number of parameters involved in the displacement process, a large number of dimensionless scaling groups can be defined. For stable displacements, an inspectional analysis of the partial differential equations for describing the displacement process provides the following scaling groups (Peters, 1988):

a. $M = \dfrac{k_{wor}\,\mu_o}{k_{oiw}\,\mu_w}$

b. L/D

c. k_{rw}

d. k_{ro}

e. $\dfrac{V\ \mu_w\ D}{\sigma\ \sqrt{k\phi}}$

f. $\dfrac{V\ \mu_w\ L}{\sigma\ \sqrt{k\phi}}$

g. $\dfrac{dJ}{dS_w}$

Based on his linear perturbation analysis for the onset of instability, he suggested that only the following dimensionless groups are pertinent to unstable displacements:

$$M;\ k_{rw};\ k_{ro};\ \frac{\sqrt{k}}{D}\ ;\ \frac{V\ \mu_w\ D}{\sigma\ \sqrt{k\phi}}\ ;\ \frac{dJ}{dS_w}\ .$$

It is interesting to note that the only geometric factor present in the above list of dimensionless factors is the diameter. This implies that the system length and the length/diameter ratio are not relevant parameters for the onset of instability. However, due to the fact that the stability analysis does not account for conditions prevailing under fully developed fingers, the length/diameter ratio may be an important parameter in growth and propagation of viscous fingers.

Pavone (1989) used the capillary number difference $\Delta C_a = \dfrac{(\mu_o - \mu_W)\ V}{\sigma}$ and viscosity ratio μ_o/μ_w for correlating his data on performance of unstable displacements.

OBJECTIVES

Although viscous fingering has been studied by many, the data reported in the literature are not complete enough for developing an empirical model for predicting pseudo relative permeabilities. In most cases the experimental displacements were terminated soon after water breakthrough and the systems used were inadequately characterized. Therefore, it is necessary to conduct carefully controlled experiments before the available models can be tested and new models can be developed. The goal of this work was to combine the information available in the literature with our own experimental data to develop simple models for predicting oil recovery in unstable displacements. We were primarily interested in evaluating the use of pseudo-relative permeability, which can be used directly in commercial computer simulation programs, to describe the macroscopic performance of unstable floods. The main objective was to examine the relationship between the pseudo-relative permeability and the operational parameters of the unstable displacements.

EQUIPMENT, MATERIALS AND METHODS

As discussed in the literature review section, the displacement process is affected by a large number of variables including: oil/water viscosity ratio; flood velocity; interfacial tension; absolute permeability; and physical dimensions of the system. A complete experimental examination of the effects of all these variables was not within the scope of this work. Therefore, only three variables were selected for detailed examination; (1) oil/water viscosity ratio; (2) flood velocity; and (3) the physical dimensions of the displacement system. To further reduce the number of experiments required, the effect of system geometry was examined at fixed values of the viscosity ratio and the flood velocity. Likewise, the system geometry was kept constant in the experimental evaluation of the effects of flood velocity and viscosity ratio.

EQUIPMENT

Two different rigs were used to carry out the oil displacement experiments. These are described briefly in the following.

Rig #1:

This experimental setup, shown schematically in Figure 1, was designed for linear core flood experiments. It comprised a Ruska positive displacement pump, a flow multiplier, a transfer vessel, a core holder, an electronic differential pressure transducer, a high pressure visual separation cell and a back pressure regulator. Several different core holders were used to investigate the effects of the core length and core diameter.

Rig #2:

This apparatus was designed for visualization of the viscous fingering in the displacement process. Figures 2 and 3 show schematic diagrams of this rig. The porous medium used in this apparatus was a 1 cm thick bed of spherical glass beads sandwiched between a 5cm thick glass plate and a stainless steel plate. The bed was 50 cm long and 20 cm wide. The stainless steel plate accommodated all fittings including, the inlet and outlet ports and a filling plug for packing the glass beads. The model was mounted on a robust pivoting stand to facilitate experiments at angles other than the horizontal. Two HPLC constant rate pumps were used to inject oil and water into the model. The volume of oil produced during the displacement experiments was monitored by flowing the effluent fluids through a separator cell which trapped the oil phase.

MATERIALS

Porous Media:

Linear core flood experiments were carried out in sand packs prepared with Ottawa sand. The dimensions and petrophysical properties of the sandpacks used are listed in Table 1. The visual model was packed with class IVA-203 glass beads manufactured by Ferro Corporation. The dimensions and relevant properties of this porous pack are listed in Table 2.

Fluids:

Three different mineral oils -- Tellus-320, Vitrea-150, Vitrea-22 -- were used to evaluate the effect of oil viscosity. The properties of these three oils, relevant to this study are given in Table 3. The density and viscosity measurements were taken from manufacturer's data sheets. The interfacial tension measurements between the given oil and water were carried out using the

technique described by Mannhardt [11].

The displacing fluid was deionized water. For experiments in the visual model, a small amount (ppm level) of Acid-Violet 17, a purple dye manufactured by Aldrich, was added to the deionized water. The dye was insoluble in oil, and as a result, the oil/water interface was visually discernable through the glass plate of the flow-visualization model.

RESULTS AND DISCUSSION

A. DISPLACEMENTS IN TUBULAR GEOMETRY

These tests were carried out in sandpacks of different length and diameter. The main objective was to evaluate the effect of geometric factors on the displacement performance. Accordingly, other parameters were held constant. Same sand-fluid system was used in all tests and the displacement velocity was maintained as close to the nominal value of 8.0 m/d as practical with the available equipment. A summary of the test conditions is provided in Table 1. The core length was varied from 9.8 cm to 127.0 cm. The core diameter ranged from 1.3 cm to 9.2 cm. The L/D ratio was varied by two orders of magnitude in these tests.

Table 4 summarizes the results of the oil displacement tests in tubular geometry. Minor differences were noted in the petro-physical properties of the different sandpacks used in these tests. Although the same sand was used in all sandpacks, the absolute permeability varied from 2.77 D to 4.2 D. The initial water saturation was generally between 0.05 and 0.09, except for the very small diameter packs where it varied from 0.02 to 0.12. All displacements were carried to at least 10 pore volumes of water injection. The oil recovery at 10 pore volumes injected varied from 0.38 to 0.55.

The recovery and pressure drop data for each displacement were history matched using a computer program called PRISIM, which was developed at the Petroleum Recovery Institute for the purpose of calculating relative permeabilities from displacement data (Sigmund and McCaffery, 1979). The values of the adjustable and fixed parameters used for obtaining acceptable history matches are tabulated in Appendix A along with the comparison of the

experimental and calculated values of the displacement data and the inferred pseudo-relative permeabilities. Although there were minor differences in the initial water saturation in different runs, it was assumed that the irreducible water saturation was the same in all runs. The displacements were terminated before the oil production had completely ceased. To account for this the maximum possible water saturation was fixed at 70% in all simulations. Thus, the adjustable parameters for history matching were, the end point relative permeability to water (at 70% water saturation) and the exponents of oil and water relative permeabilities.

EFFECT OF GEOMETRIC FACTORS ON PSEUDO-RELATIVE PERMEABILITY

To evaluate the effects of sandpack diameter and length on the pseudo-relative permeability, the pseudo-relative permeability curve can be broken into six constituent parameters: S_{wi}; k_{roiw}; S_{or}; k_{rwor}; ϵ_w; and ϵ_o. Of these, S_{wi} and k_{roiw} are fixed prior to water injection and do not depend on the stability of the waterflood. Therefore, these parameter were held constant in calculating the pseudo-relative permeabilities. The value of S_{or} and the spatial distribution of the residual oil can depend on the flow instabilities. However, as noted by Maini and Okazawa (1987), the true S_{or}, can only be determined by injecting a very large number of pore volumes. Its value can not be determined by history matching alone. For this reason, the value of S_{or} was kept constant at 30%, which was the average extrapolated value. Thus, the effects of geometric factors on the pseudo-relative permeability can be characterized by three parameters: k_{rwor}; ϵ_w and ϵ_o.

Figure 4 shows a plot of the endpoint water relative permeability against the length/diameter ratio. It is apparent that the endpoint water permeability does not correlate well

with the L/D ratio. The relationships between the exponents of the oil and water relative permeabilities and the L/D ratio are shown in Figures 5 and 6. These parameters also correlated poorly with the L/D ratio. Therefore, it was concluded that L/D ratio may not be a pertinent dimensionless number for describing the behaviour of these unstable displacements. However, experiments with different mobility ratio systems over a much wider range of L/D ratio and at varying flow velocities are needed to draw firm conclusions.

The other dimensionless number tested was $\frac{D}{\sqrt{k\phi}}$. Figures 7, 8 and 9 respectively show the relationship between this parameter and k_{rwor}, ϵ_w and ϵ_o. Once again, the correlations were not satisfactory. Several other dimensionless numbers containing the diameter and/or length were tried, but none produced satisfactory correlations. It was concluded that the effect of the geometric factors on pseudo-relative permeabilities was less significant than the experimental scatter in the data which could have resulted from minor differences in the petrophysical properties of different sandpacks.

EFFECT OF GEOMETRIC FACTORS ON BREAKTHROUGH RECOVERY:

Figures 10 and 11 show the breakthrough recovery plotted against L/D ratio and the parameter $\frac{D}{\sqrt{k\phi}}$. The breakthrough recovery appears to be independent of these dimensionless numbers. This is consistent with the findings of Peters and Flock (1979) who found the breakthrough recovery to be independent of the stability number (Equation 4) at high values of their stability number. The estimated values of the stability number for these displacements were mostly in the pseudo-stable zone ($I_{SC} > 900$).

EFFECT OF GEOMETRIC FACTORS ON RECOVERY AT 10 PORE VOLUMES INJECTED:

The oil recovery at 10 pore volumes injected is plotted in Figures 12 and 13. The oil cut was about one percent at this value of injected pore volumes. It is apparent that the value of oil recovery at flood-out conditions was also independent of the geometric factors.

B. DISPLACEMENTS IN RECTANGULAR GEOMETRY WITH FLOW VISUALIZATION

A total of 21 displacement runs were carried out in the flow visualization model as outlined in Table 5. Runs 1-5 were used to determine the effect of flow rate on oil recovery in this study. Unfortunately, in Run 1 the method of measuring the amount of fluid produced was still being perfected, and as a result, was not reliable. Consequently, Run 1 could not be used for comparison purposes.

Runs 6-11 were carried out to determine the effect of initial wetting condition on oil recovery. To achieve an initial water saturation of zero, the model was blown dry with nitrogen and then saturated with the oil.

Runs 12-15 were carried out using a different mineral oil to determine the effect of viscosity of the displaced phase on oil recovery. The evaluation of the effect of viscosity was continued in Runs 16-19, which were conducted using the least viscous of the three mineral oils.

To study the effects of gravity on oil recovery, the model was angled at 45° {Runs 20,21}.

The experimental results for the immiscible displacement runs are summarized in Table

6.

Effect of Displacement Rate on Oil Recovery:

Figures 14 through 16 show the effect of displacement rate on cumulative oil recovery for three different oils. The cumulative amount of oil recovered, at a given time, t, increases as the rate of injection of the displacing phase into the system increases for the high viscosity oils. A plausible explanation of this effect of flow rate, which is clearly noticeable in Figures 14 and 15, is the possible gravity segregation of the injected fluid for runs that had low flow rates. The degree of gravity segregation of the injected fluid is dependent upon the ratio of gravity forces to viscous forces, ie. $\Delta P_v/\Delta P_h$ (Craig, 1980). As the flow rate is increased, the viscous forces become stronger and suppress gravity segregation. However, Figure 16 shows that the effect of flow rate is not so clear-cut in the case of the lowest viscosity oil, Vitrea 22. From Table 3, it becomes apparent that the viscosity ratio for this oil and water is much less than either Vitrea-150, or Tellus-320 and water while the density of Vitrea-22 is significantly less than that of the other two oils. The lower density would normally result in increased gravity segregation. However in this case, the effect of increased density difference is nullified by the effect of reduced viscosity ratio. The viscosity ratio has a pronounced effect on the extent of viscous fingering, which in turn affects oil recovery.

Effect of Viscosity Ratio on Oil Recovery:

Figures 17 through 20 show the effect of oil viscosity on cumulative oil recovery at four different flow rates. As expected, the least efficient displacements, at any given time, t, were

observed with the most viscous oil, Tellus-320. Both, the breakthrough recovery and the ultimate recovery, are affected by the oil viscosity.

Effect of the Initial Wetting Condition on Oil Recovery:

The effect of initial wetting condition on cumulative oil recovery at three different flow rates is presented in Figures 21 through 23. At the lowest flow rate (2 ml/min) the initial wetting condition had a significant effect on the breakthrough recovery but very little effect on the final recovery. However, at higher flow rates, the oil-wet runs (ie. an initial water saturation of zero) gave significantly higher final oil recoveries.

Effect of Gravity:

The effect of gravity on cumulative oil recovery at 4 mL/min is displayed in Figure 24 which compares the recovery performance of a up-dip displacement at 45° angle with a horizontal displacement. A significantly greater amount of oil was recovered when the model was positioned at an angle. In the up-dip displacement, the gravitational forces exert a stabilizing influence and reduce the extent of flow instability. This was confirmed by the presence of a more even front with less viscous fingering in the run angled at 45 degrees as compared to the horizontal run.

Effect of Capillary Number:

Capillary forces can have a significant impact on displacement of oil in a reservoir. The capillary number difference given in the equation below has been used in previous studies

(Pavone, 1989; Sarma et al., 1990) to characterize the effect of the ratio of capillary forces/ viscous forces:

$$\Delta C_A = \frac{(\mu_o - \mu_w)v}{\sigma} \qquad (10)$$

The advantage of using capillary number difference instead of capillary-number is that both the viscous forces of the oil and water are accounted for in the displacement process. Presented in Figure 25 are plots of breakthrough recovery versus capillary number difference for the three different oils. It shows that for the same oil viscosity, the amount of oil recovered at the breakthrough of the displacing fluid increases with increasing capillary number. However, when the capillary number difference is increased by increasing the oil viscosity, the breakthrough recovery decreases. Therefore, it can be concluded that the capillary number difference alone is not sufficient to characterize the displacement behaviour.

Pseudo-Relative Permeabilities:

Pseudo-relative permeabilities were calculated using the same technique as discussed above for the tubular systems. Figures 26 through 29 illustrate the effect of displacement rate on the relative permeability curves for four different systems. In general, the flow rate has a more pronounced effect on the water relative permeability than on the oil relative permeability. The end point water permeability increases with increasing flow rate. Figures 30 through 33

show the effects of viscosity ratio on relative permeability estimates at four different flow rates. As expected, the increase in the viscosity of the oil in the core had little to no effect on the oil relative permeabilities. However, with increasing oil viscosity, and thereby increasing viscosity ratio, the water permeability curve significantly declined. This observation is in agreement with findings in a previous study by Lefebvre du Prey (1973) who reported that increasing viscosity of one phase led to a decline in the relative permeability curve of the other phase.

Effect of Instability Number on Breakthrough Recovery:

Figure 34 presents a plot of the amount of oil recovered at breakthrough versus the instability number for four different systems. The instability number was calculated using the following equation proposed by Bentsen (1985):

$$I_{ar} = \frac{\mu_w v(M-1-N_g)}{\sigma_e K_{wor}} \cdot \frac{M^{5/3}+1}{(M+1)\cdot(M^{1/3}+1)^2} \cdot \frac{4h^2L_y^2}{h^2+L_y^2} \qquad (11)$$

Where

$\sigma_e = C^* \cdot \sigma$

C^* - *Wettability number*

The interfacial tension values can be found in Table 3. In order to calculate the effective interfacial tension, the wettability numbers used for this calculation were 5.45 for water-wet media and 306.25 for oil-wet media. These numbers were taken from a previous study by Peters and Flock (1981).

The figure shows that there appears to be some consistent trend in R_{bt} in stable and pseudo-stable regions, shown by the dashed lines. However, the unstable region showed a wide

scatter. Most of the runs with I_{sr} values between 2 and 9 show lower R_{bt} values than expected. The use of an incorrect estimate for the wettability number may be partly responsible for this discrepancy. However, our experimental data for the intermediate viscosity oil shows increasing breakthrough recovery with increasing instability number and this trend will remain intact irrespective of the value chosen for the wettability number. The wettability number must be made a function of the flow velocity before such data can be reconciled with the instability theory. Such possible dependence of wettability number was also observed by Sarma (1986).

CONCLUSIONS

The results presented above show that the macroscopic behaviour of unstable displacements can be modelled by the Buckley-Leverett displacement theory, provided that appropriate pseudo-relative permeability curves are used in place of the true relative permeabilities. The dependence of such pseudo-relative permeability curves on several system variables was investigated. Although, the evaluated correlations for describing the dependence of pseudo-relative permeability were found to be unsatisfactory, certain broad generalizations can be made regarding the nature of such pseudo-relative permeabilities.

1. The effect of L/D ratio on pseudo-relative permeability was smaller than the experimental scatter in the data. However, since the instability number of these displacements was very high (in pseudo-stable region), this observation may not apply to moderately unstable displacements.
2. The end-point water permeability increases with increasing flow velocity.
3. The end-point water permeability and the final oil recovery decrease with increasing oil viscosity.
4. For very adverse viscosity ratio, both the breakthrough recovery and the final recovery increase with increasing displacement rate.
5. The Buckley-Leverett frontal advance theory, in conjunction with the use of pseudo-relative permeability curves, can be used to describe the megascopic behaviour of immiscible displacements involving viscous fingering.

6. It is suggested that the wettability number proposed by Peters and Flock is not constant for a particular rock-fluid system, but rather, it may be a function of the flood rate.

NOMENCLATURE

A	area of the porous medium
c^*	wettability number
ΔC_a	capillary number difference
D	diameter
g	gravitational acceleration.
h	height of the porous medium
I_{sc}	instability number for a cylindrical system
I_{sr}	instability number for a rectangular system
I_{st}	Bentsen's instability number for a cylindrical system
k_{oiw}	permeability to oil at connate water saturation
k_{wor}	permeability to water at residual oil saturation I_{sr} instability number
ΔL	change in length of the core
L	length of cylindrical core
L_y	length of the porous medium
M	mobility ratio
N_g	gravity number
N_{Pb}	breakthrough recovery
ΔP_f	drop in pressure across the core at run's end
ΔP_i	initial drop in pressure across the core
q	flow rate
R_{bt}	recovery at breakthrough

S_{or}	residual oil saturation
S_{wi}	initial water saturation
T_{bt}	time to breakthrough
V	velocity of the injected phase
V_c	critical velocity
θ	angle between the displacement direction and the vertical
λ_c	critical wavelength of perturbation
λ_m	wavelength of maximum instability
μ_o	viscosity of oil
μ_w	viscosity of water
ρ_o	density of oil
ρ_w	density of water
σ	interfacial tension
σ_e	pseudo-interfacial tension

REFERENCES

Bentsen, R.G. (1986): "Use of Capillary Pressure Data to Estimate the Pseudo-interfacial Tension for Analysis of Stability of Fluid Flow in Porous Media", AOSTRA J. of Res., (December 1986), 213.

Bentsen, R.G. (1985): "A New Approach to Instability Theory in Porous Media" Soc. Pet. Eng. J. 25, 765

Buckley, S.E., and Leverett, M.C. (1942): "Mechanism of Fluid Displacement in Sands" AIME Trans., 146, 107.

Chakrabarty, C. and Bentsen, R.G. (1991): "Instability Theory for Immiscible Displacements in Tubular Systems", To be published in AOSTRA J. of Res.

Chuoke, R.L., van Meurs, P and van der Poel, C. (1959): "The Instability of Slow, Immiscible, Viscous Liquid-Liquid Displacements in Permeable Media", Trans AIME, 216, 188-194

de Haan (1959): "Effect of Capillary Forces in the Water Drive Process", Proc. Fifth. World. Pet. Cong., Sec II. 319-335.

Engelberts, W.F., and Klinkenberg, L.J. (1951): Laboratory Experiments on Displacement of Oil by Water from Rocks of Granular Materials", Proc. Third World Pet. Congress., Part II, 544-554.

Gupta, S.P., and Greenkorn, R.A. (1974), "An Experimental Study of Immiscible Displacement with an Unfavourable Mobility Ratio in Porous Media", Water Resour. Res. 10, 371-74.

Hagoort, J. (1974): "Displacement Stability of Water Drives in Water-Wet Connate Water Bearing Reservoirs", Soc. Pet. Eng. J. (Feb) 63-74.

Homsy, G.M.(1987) "Viscous Fingering in Porous Media", Ann. Rev. Fluid. Mech. 19. 271.

Hughes, D.S. and Murphy, P. (1987): "Accounting for Unstable Immiscible Flow Within a Conventional Reservoir Simulator by Use of Pseudo-Relative Permeabilities", Presented at the 4th BASF Ag et al. Enhance Oil Recovery European Symposium, (Hamburg, Ger. October 27-29.

Maini, B.B. and Coskuner, G. (1988): "Measurements of Viscous Oil-Water Relative Permeability of Sand: Effects of Flow Rate and Temperature", Proceedings of The Fourth UNITAR/UNDP International Conference on Heavy Crude and Tar Sands, Vol. 2, pp. 759-774.

Maini, B.B. and Okazawa, T. (1987): "Effect of Temperature on Heavy oil-Water Relative Permeability of Sand", J. Can. Pet. Tech. (May-June) pp 33-41.

Muskat, M. (1937): "Flow of Homogeneous Fluids through Porous Media", McGraw-Hill, New York.

Pavone, D.(1989): "Observations and Correlations for Immiscible Viscous Fingering Experiments", SPE Paper 19670, presented at the 64th Annual Tech Conference of SPE, San Antonio, TX, Oct. 8-11, 1989

Perkins, T.K., and Jonston, O.C. (1969): "A Study of Immiscible Fingering in Linear Models", Soc. Pet. Eng. J. (March) 39-46.

Peters, E.J., and Flock, D.L. (1979), "The Onset of Instability During Two-Phase Immiscible Displacements in Porous Media", SPEJ (April) 249-259.

Peters, E.J. and Khataniar, S. (1987): "The Effect of Instability on Relative Permeability Curves Obtained by Dynamic-Displacement Method", SPE Form. Eval. (December) 469-473.

van Meurs, P. (1958): "The Use of Transparent Three Dimensional Models for Studying the Mechanism of Flow Processes in Oil Reservoirs", Trans AIME 213, 103.

Vossoughi, S. and Seyer, F.A. (1984): "Prediction of Recovery and Water Saturation Distribution During an Unstable, Immiscible Displacement of Oil from a Porous Medium" Ind. Eng. Chem. Fundam. 23, 64-74.2

TABLE 1: SUMMARY OF TESTS FOR EVALUATING THE EFFECT OF GEOMTRIC FACTORS

Run Number	3	2	5	6	1	4	7	10	8	9	11
Core Length, cm	9.8	11.8	20.3	25.1	31.9	44.3	38.4	98.3	25.4	63.5	127.0
Cross-sec. sq. cm	66.6	25.7	66.6	66.6	25.7	25.6	11.4	20.3	1.3	1.3	1.3
Core diameter, cm	9.2	5.7	9.2	9.2	5.7	5.7	3.8	5.1	1.3	1.3	1.3
Length/Dia. ratio	1.06	2.06	2.20	2.73	5.58	7.76	10.08	19.36	19.97	49.94	99.87
Porosity	0.359	0.343	0.344	0.353	0.340	0.358	0.352	0.335	0.392	0.385	0.391
Pore Volume, ml	234.3	103.8	465.1	590.1	278.2	406.0	154.1	666.8	12.6	31.0	62.9
Absolute Perm., D	2.77	3.41	3.27	3.33	3.58	3.49	2.98	3.23	3.41	4.27	4.32
μ_w, mPa.s	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
μ_o, mPa.s	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0
Initial S_w	0.05	0.05	0.07	0.09	0.05	0.05	0.05	0.05	0.02	0.05	0.12
Injection Rate, ml/s	0.223	0.089	0.223	0.223	0.089	0.089	0.044	0.067	0.005	0.005	0.005
Velocity, m/day	8.0	8.8	8.4	8.2	8.8	8.4	9.5	8.5	8.4	8.5	8.4

Table 2 - A: Physical Parameters of the Flow-Visualization Porous Model

Length	0.508m
Area	$0.203m^2$
Height	0.010m
Thickness of Lower Stainless Steel Plate	0.050m
Thickness of Upper Glass Plate	0.050m

Table 2 - B: Properties of the Porous Medium

Type of Beads	Class IVA-203 (Ferro Corporation)
Size Range	590 - 840 μm
Average Size	715 μm
Porosity	0.390
Absolute Permeability	95.5 darcies

Table 3: Fluid Properties at 23°C

Fluid	Density (kg/m^3)	Viscosity (mPa·s)	IFT w/H_2O (dyne/cm)
Tellus-320	885.1	717.24	7.54
Vitrea-150	879.9	419.0	13.20
Vitrea-22	857.4	41.69	11.55
Coloured Water	997.5	0.9384	---

TABLE 4: SUMMARY OF TEST RESULTS FOR OIL DISPLACEMENTS IN TUBULAR GEOMETRY

Run Number	3	2	5	6	1	4	7	10	8	9	11
L/D Ratio	1.06	2.06	2.2	2.73	5.58	7.76	10.08	19.36	19.97	49.94	99.87
S_{wi}	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
k_{rotw}	0.81	0.82	0.80	0.75	0.71	0.72	0.7	0.77	0.82	0.81	0.81
Breakthrough Recovery (PV)	0.13	0.16	0.11	0.14	0.13	0.14	0.09	0.14	0.11	0.19	0.16
Final Expt. Rec. (PV)	0.47	0.55	0.46	0.46	0.48	0.43	0.38	0.39	0.44	0.42	0.46
Extrapolated Rec. (PV)	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
S_{or} (extrapolated value)	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
k_{rorw}	0.36	0.29	0.30	0.30	0.31	0.43	0.42	0.46	0.35	0.57	0.35
e_w	3.0	3.3	2.8	3.1	2.40	2.88	1.8	2.2	1.7	3.4	4.2
e_o	1.4	0.98	1.2	1.2	0.98	1.52	1.1	1.4	1.1	1.3	0.97

Table 5: Summary of the 21 Immiscible Displacement Runs

Flow Rate (mL/min)	Oil Wet	Water Wet			
	Tellus 320	Tellus 320		Vitrea 150	Vitrea 22
	Horizontal	Horizontal	45 degrees	Horizontal	Horizontal
0.5		Run 5			
2.0	Run 9	Run 4		Run 15	Run 18
4.0	Run 8	Run 3	Run 21	Run 14	Run 19
8.0	Run 7 & Run 11	Run 2		Run 13	Run 17
10.0	Run 6 & Run 10	Run 1	Run 20	Run 12	Run 16

Table 6: Summary of Experimental Data

Pore Volume = 402 mL

Run #	P.V.'s Inj.	Rbt (mL)	M	Qo (mL)	Swi	Sor	Koiw (darcies)	Kwor (darcies)
2	5.41	16	140.4	78	0.063	0.804	89.49	17.52
3	4.18	12	111.9	73	0.063	0.816	89.49	13.97
4	2.51	21	65.7	78	0.063	0.804	89.49	8.21
5	1.72	16	37.6	60	0.063	0.849	89.49	4.70
8	5.28	16	98.4	104	0	0.742	95.50	13.10
9	6.85	22	66.8	110	0	0.727	95.50	8.90
10	5.56	32	115.0	130	0	0.677	95.50	15.31
11	5.31	25	105.3	115	0	0.715	95.50	14.03
12	5.54	64	71.2	162	0.056	0.596	90.19	15.32
13	5.76	42	63.9	146	0.037	0.636	92.00	14.03
14	5.24	22	47.3	123	0.044	0.696	91.26	10.31
15	6.93	22	37.9	134	0.049	0.666	90.81	8.21
16	5.59	92	15.1	243	0.051	0.391	90.67	32.76
17	5.95	78	13.9	234	0.064	0.419	89.36	29.72
18	2.31	90	8.6	221	0.065	0.453	89.31	18.37
19	5.04	75	10.9	236	0.056	0.414	90.07	23.48
20	5.53	28	106.5	126	0.040	0.687	91.66	13.62
21	5.04	22	95.5	112	0.037	0.721	91.96	12.25

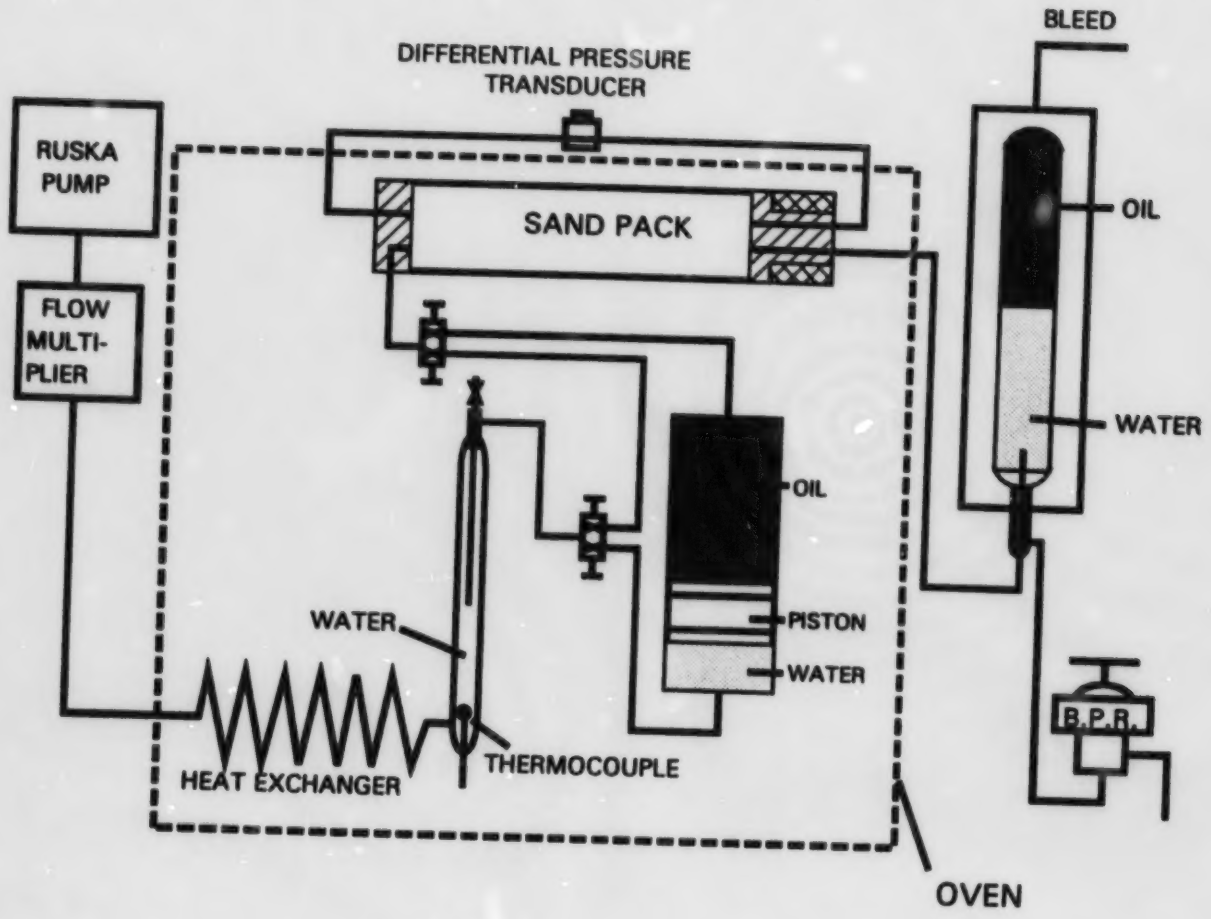


Figure 1. Schematic Diagram of the Core Displacement Apparatus

Figure 2: Schematic Diagram of the Flow-Visualization Model

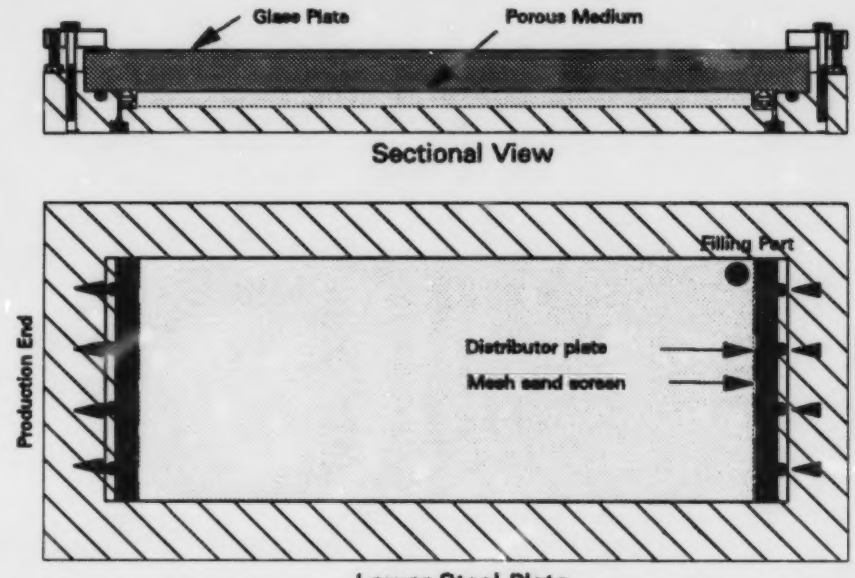
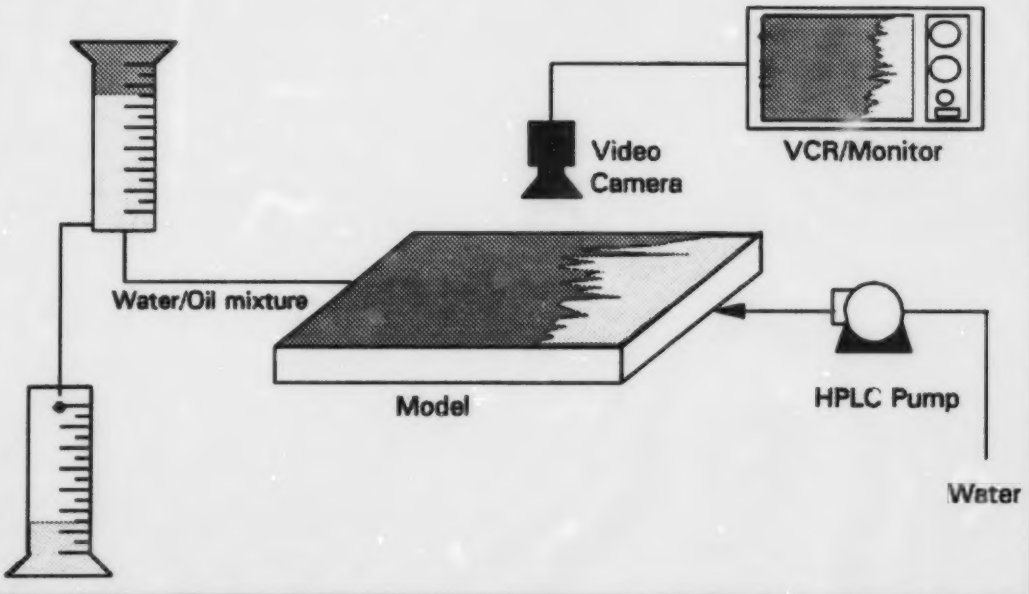


Figure 3: Schematic Diagram of the 3-Dimensional Displacement Apparatus



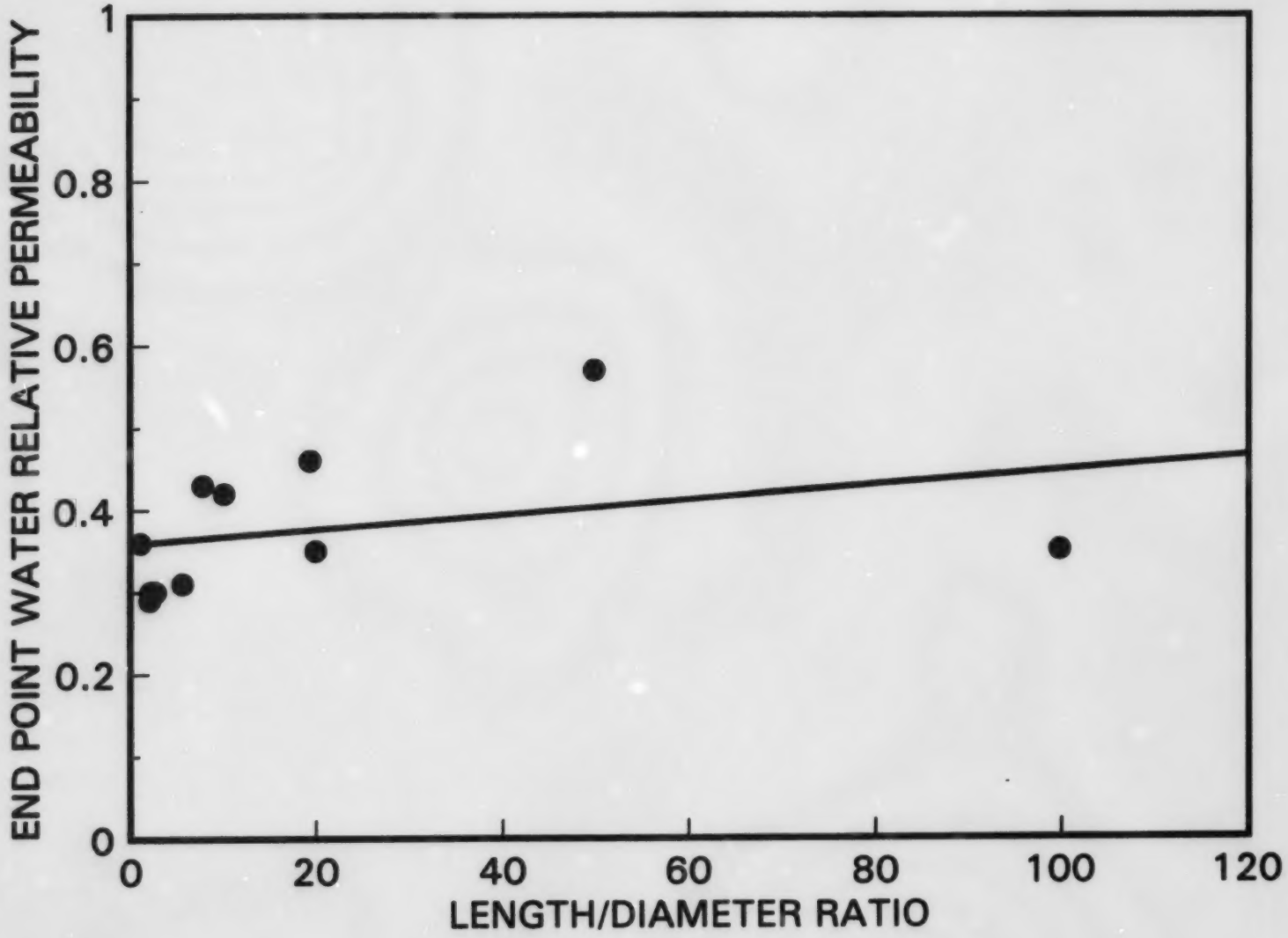


Figure 4: Effect of L/D Ratio on End Point Water Relative Permeability

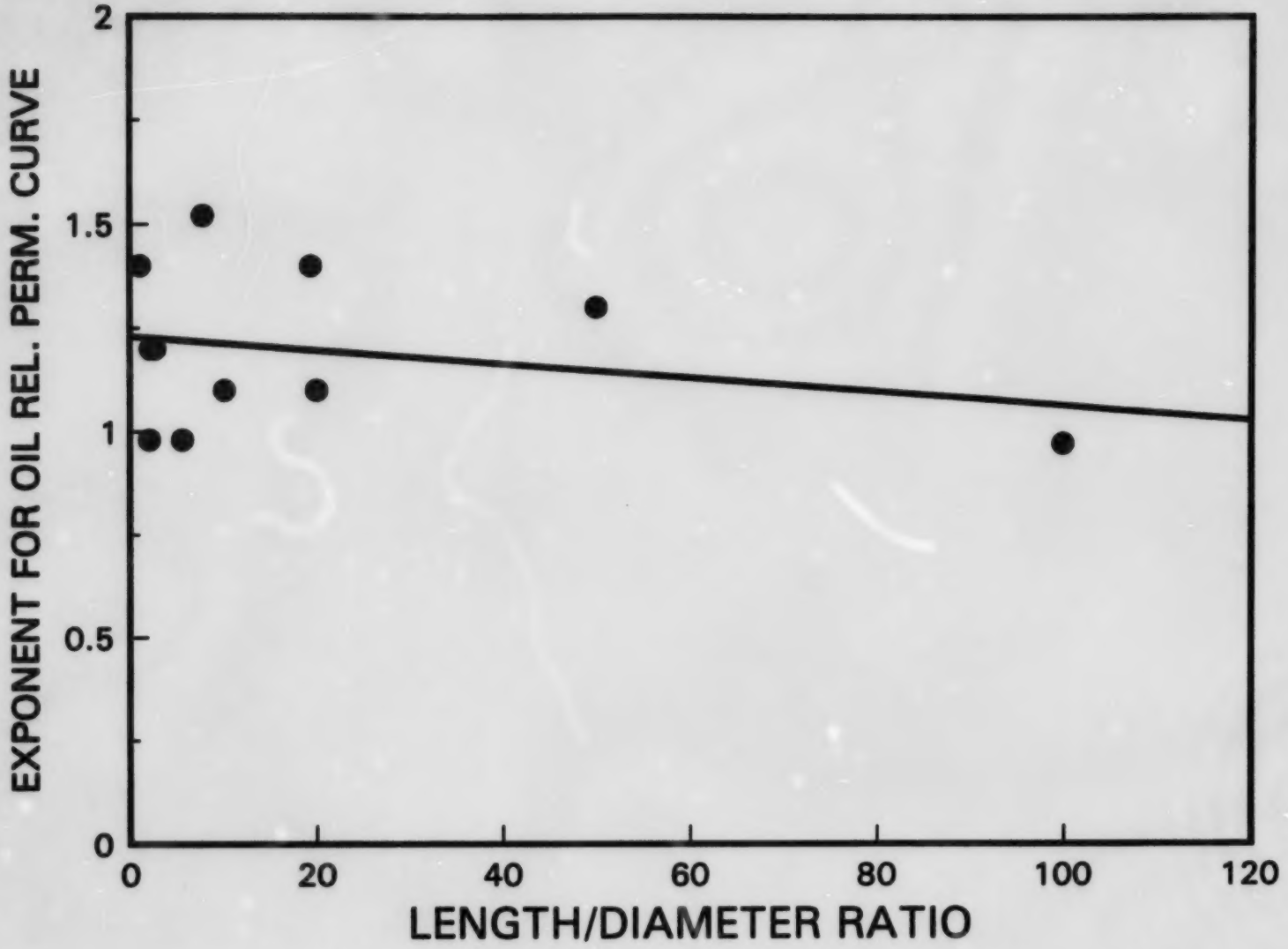


Figure 5: Effect of L/D Ratio on the Exponent of Oil Relative Permeability

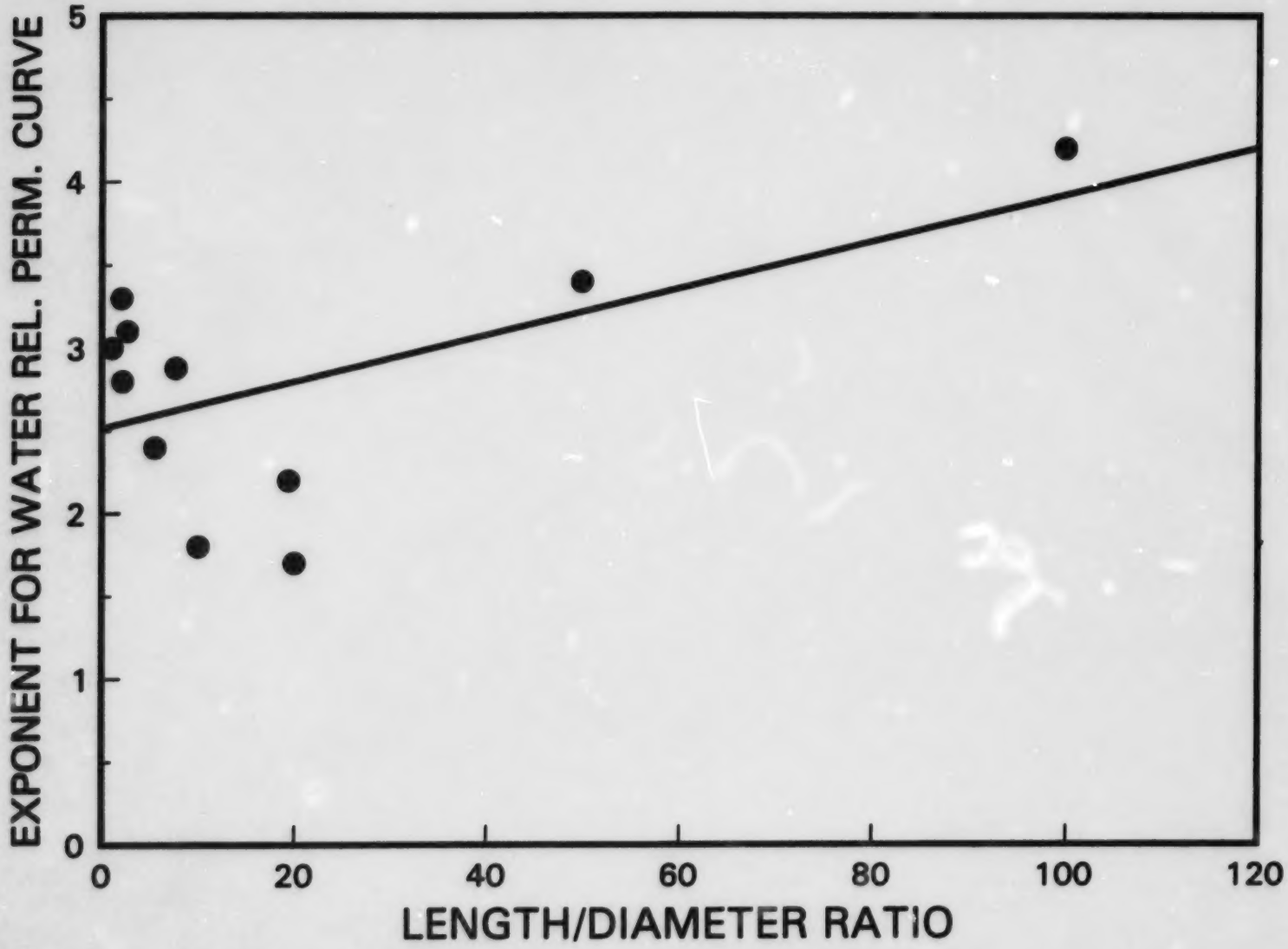


Figure 6: Effect of L/D Ratio on the Exponent of Water Relative Permeability

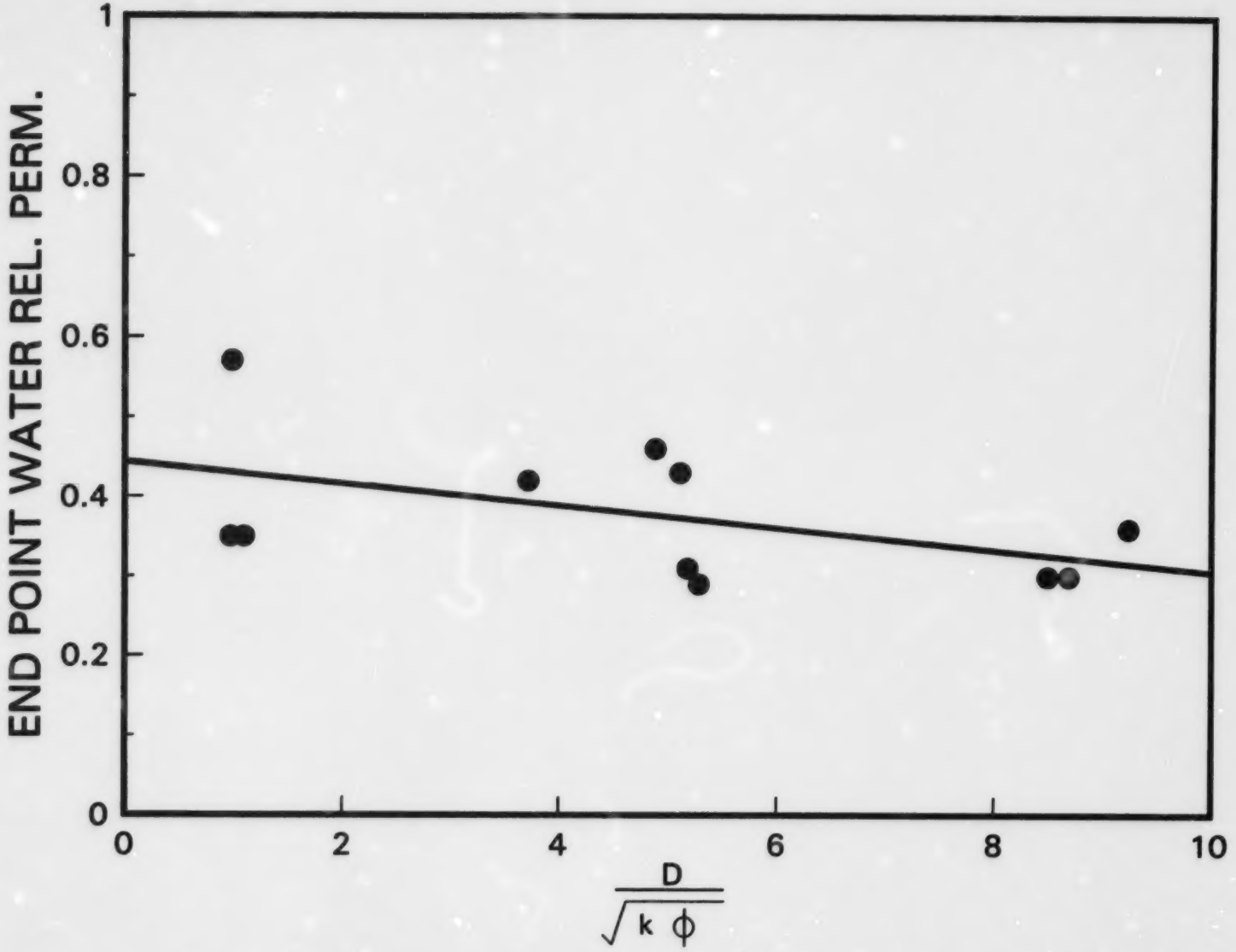


Figure 7: Effect of Diameter on End Point Water Relative Permeability

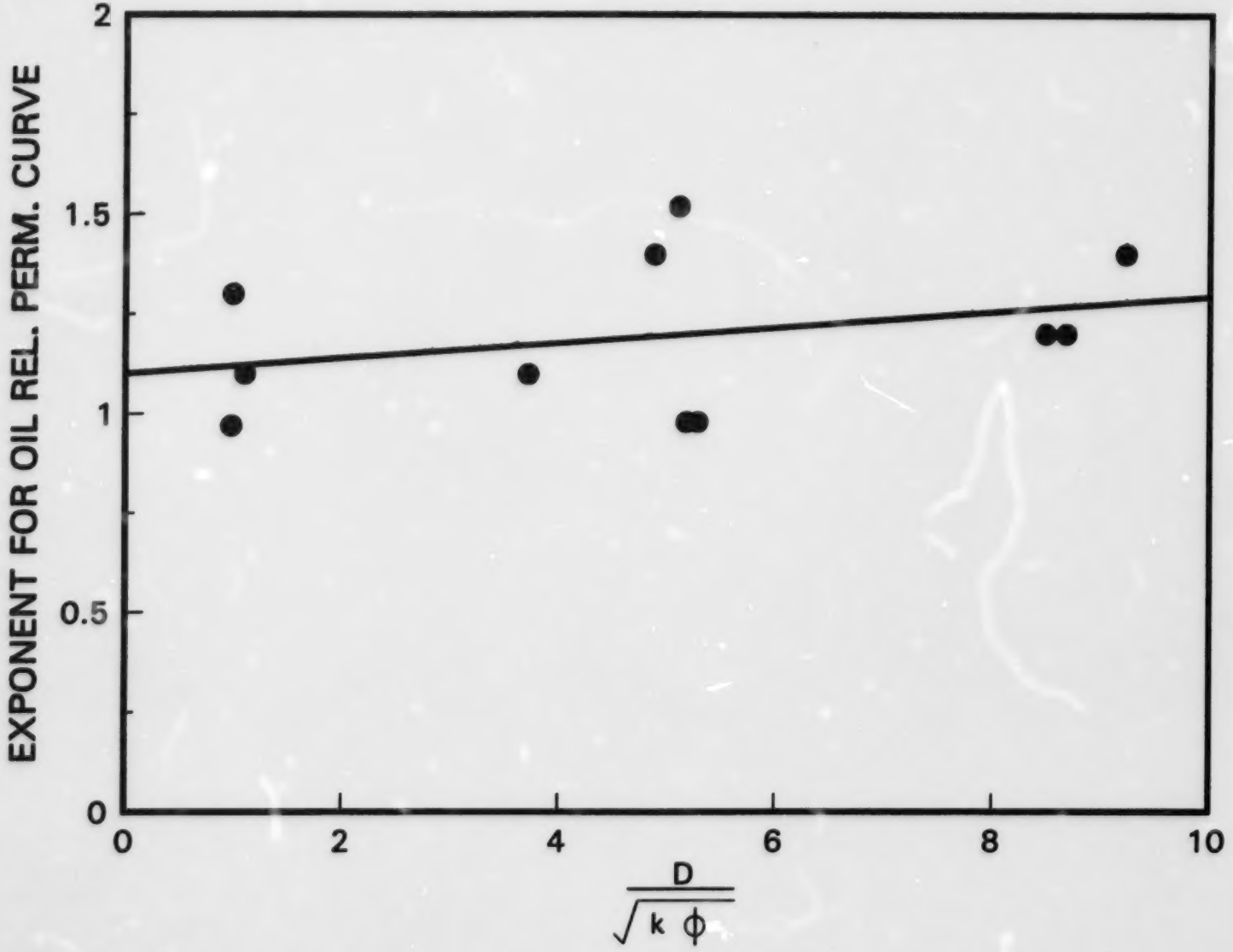


Figure 8: Effect of Diameter on Exponent of Oil Relative Permeability

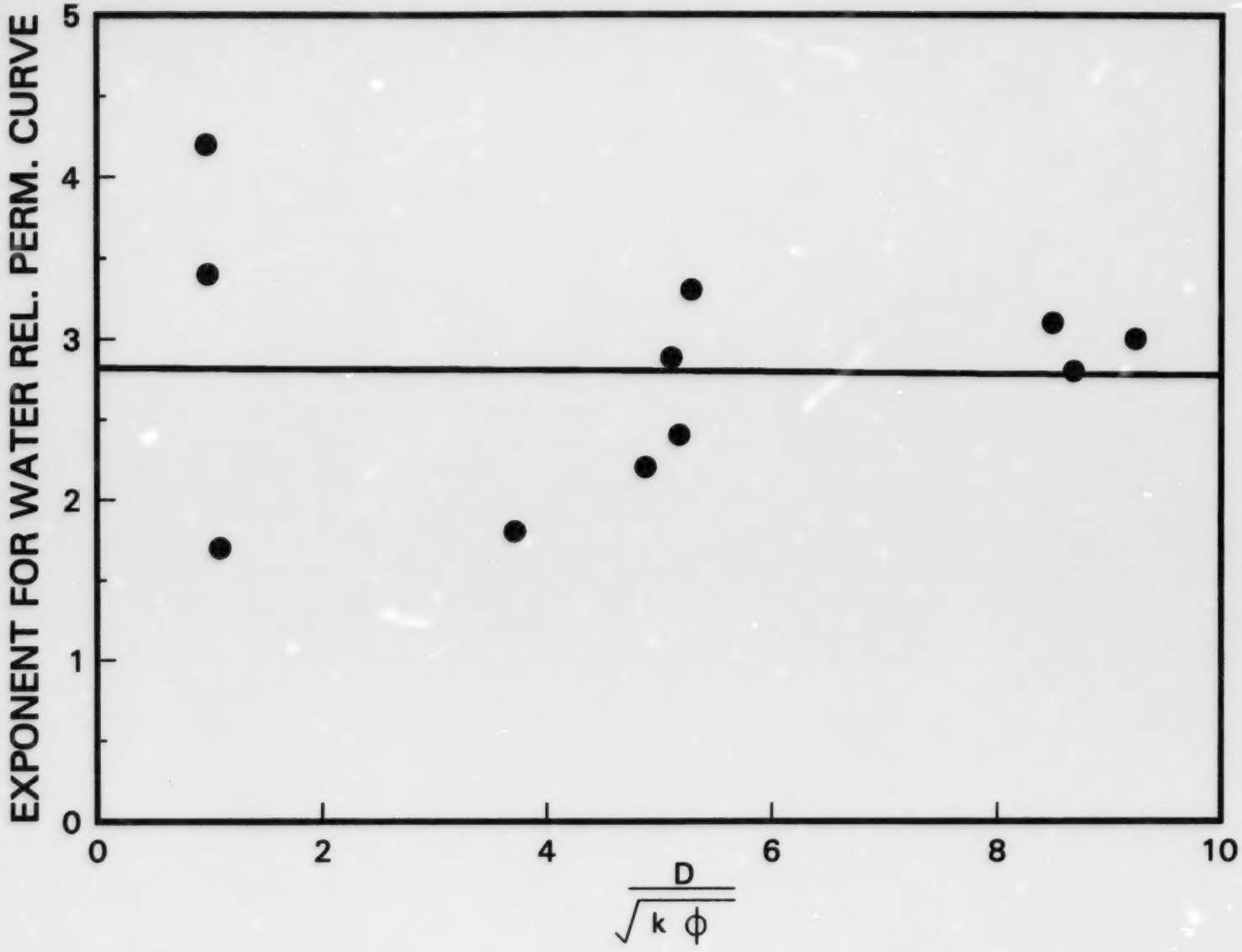


Figure 9: Effect of Diameter on Exponent of Water Relative Permeability

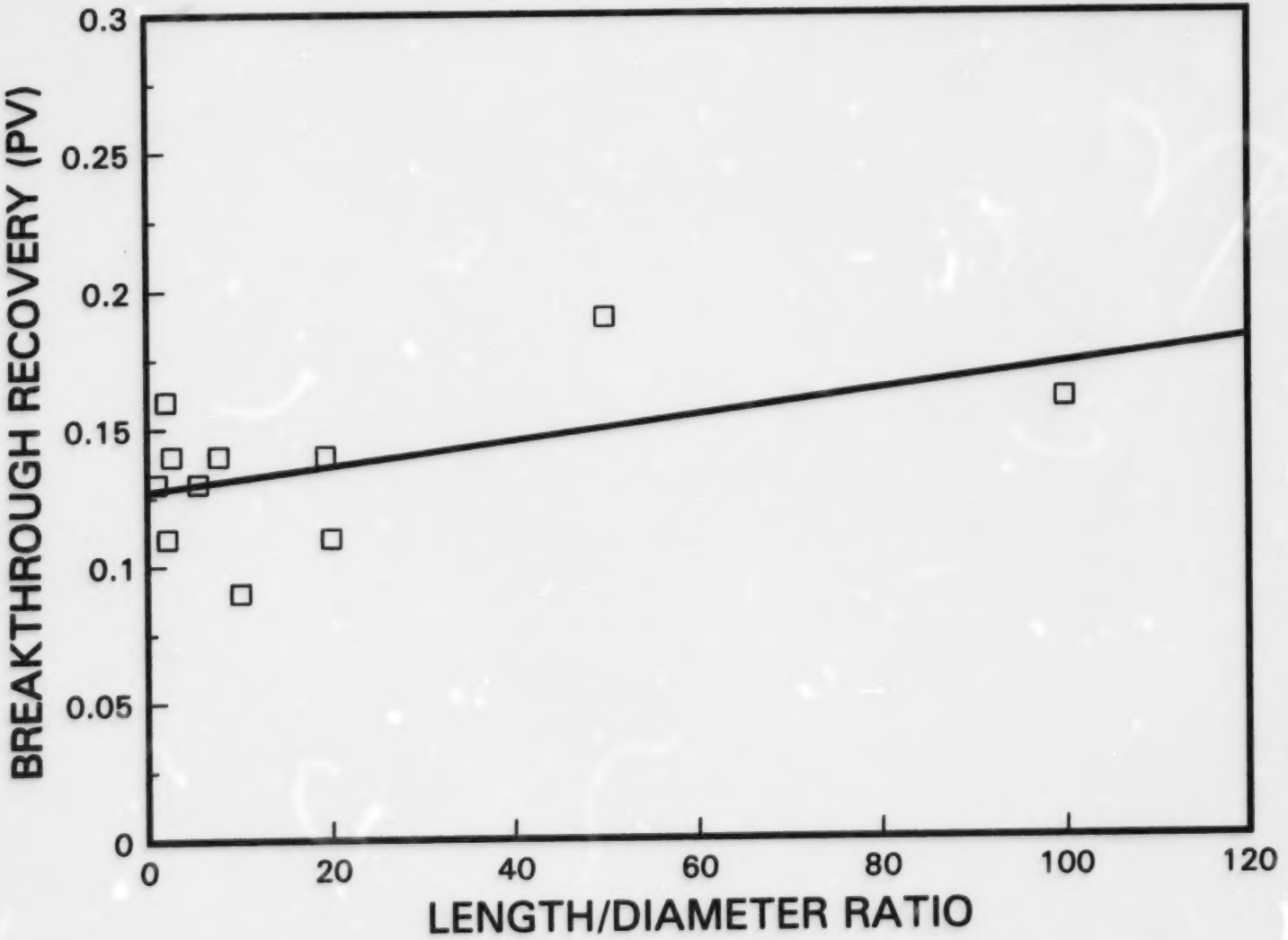


Figure 10: Effect of L/D ratio on Recovery at Breakthrough

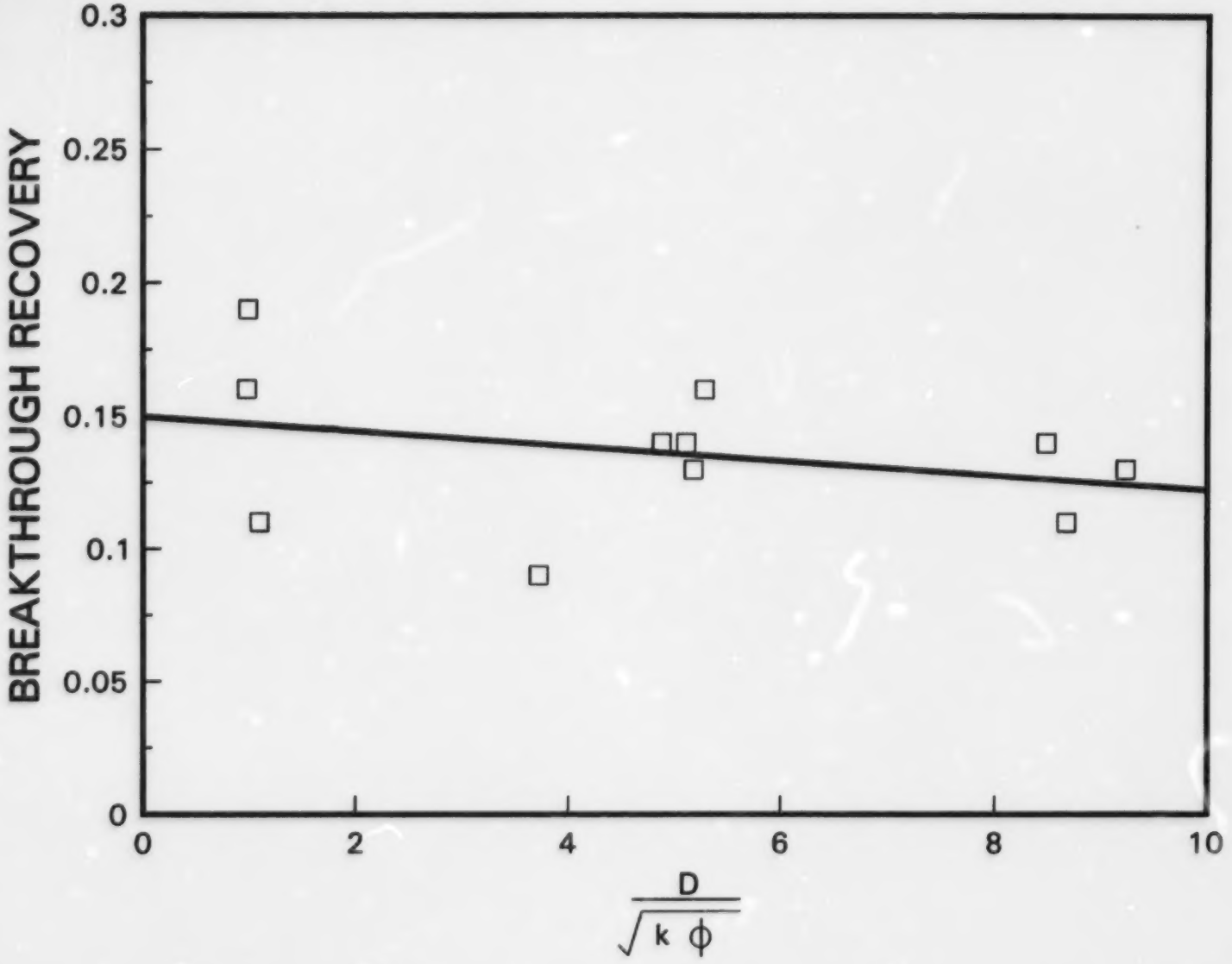


Figure 11: Effect of Diameter on Recovery at Water Breakthrough

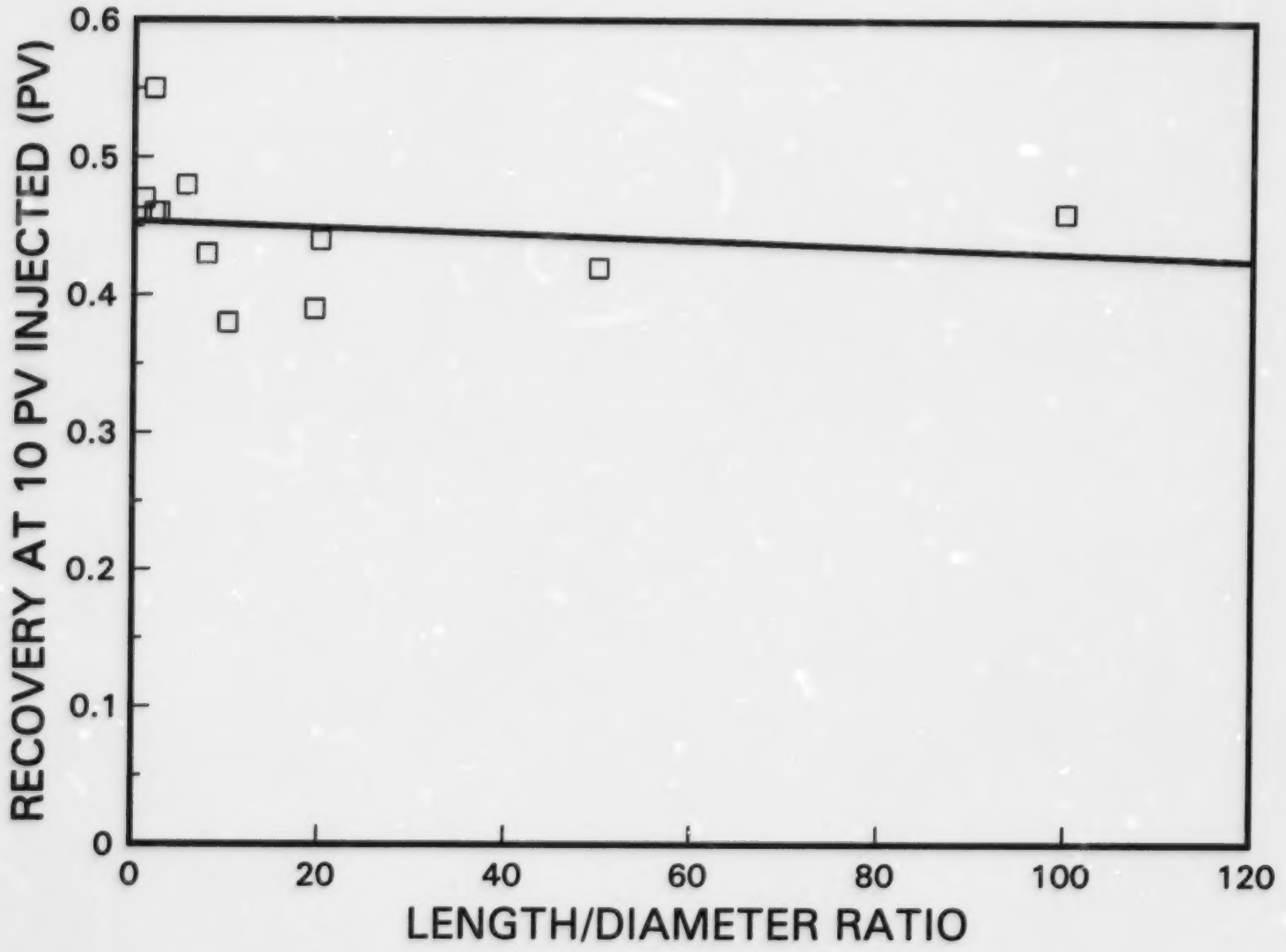


Figure 12: Effect of L/D Ratio on Recovery at 10 PV Injected

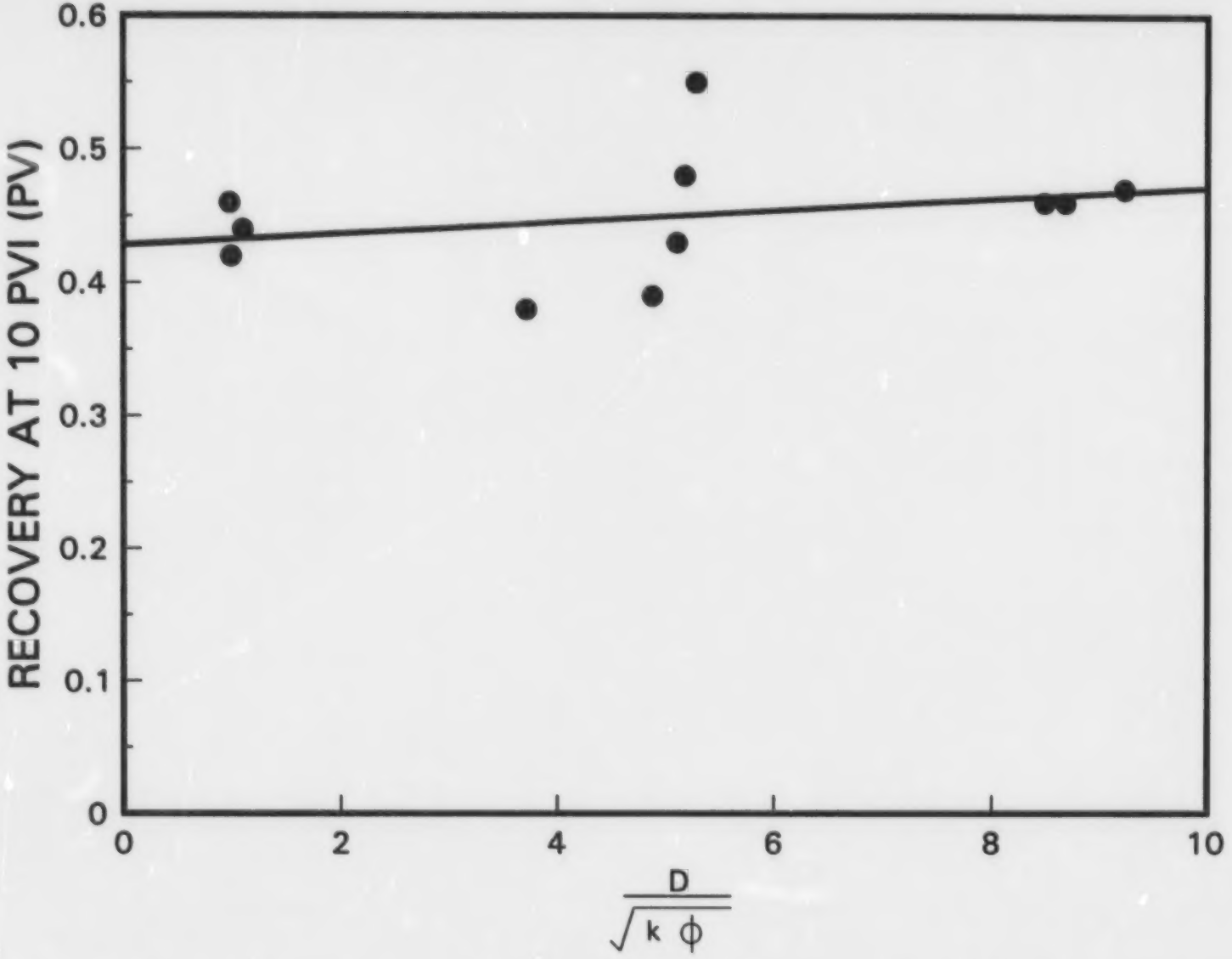


Figure 13: Effect of Diameter on Recovery at 10 PV Injected

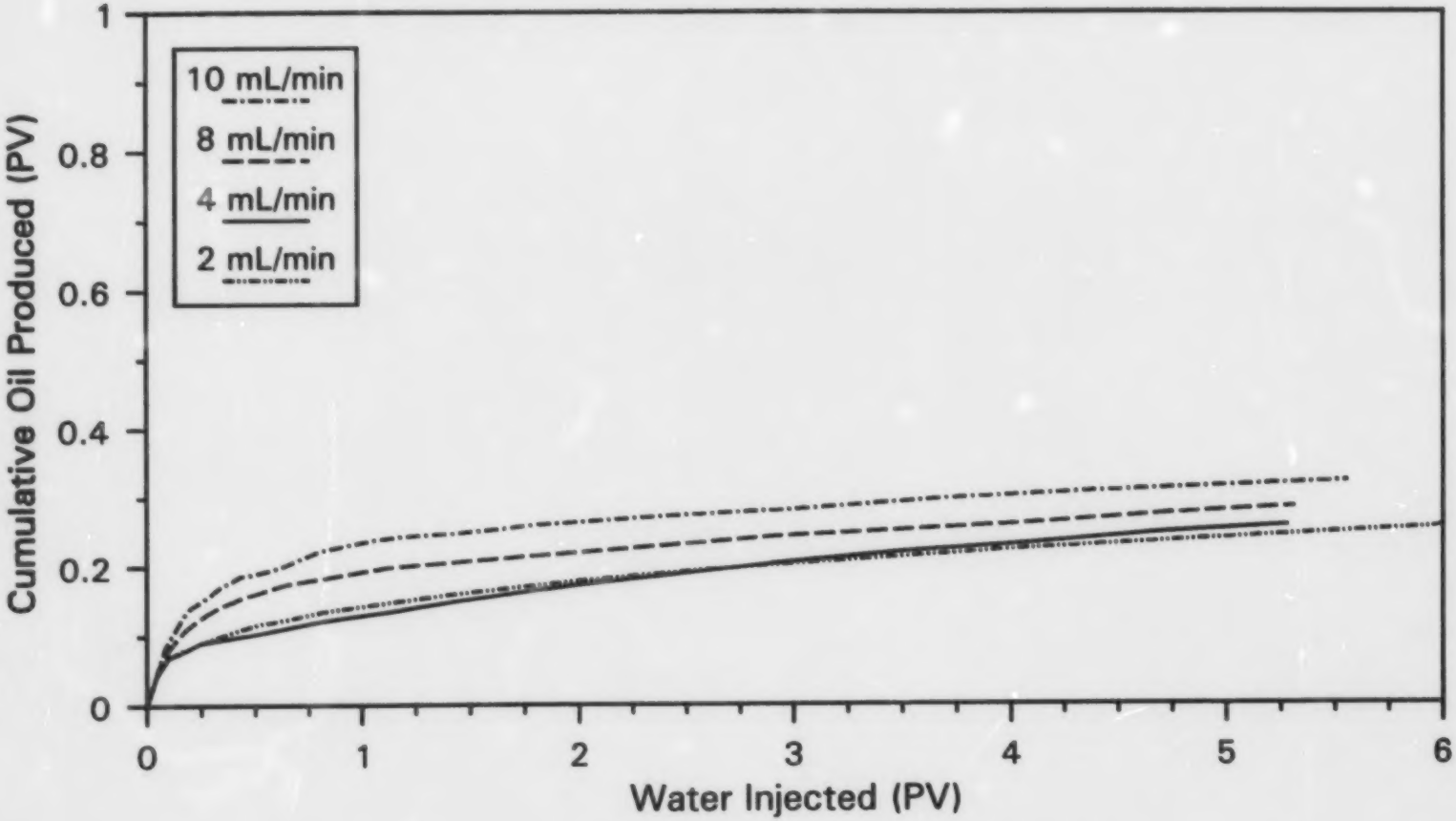


Figure 14: Effect of Displacement Rate on Oil Recovery

(Viscosity Ratio = 717)

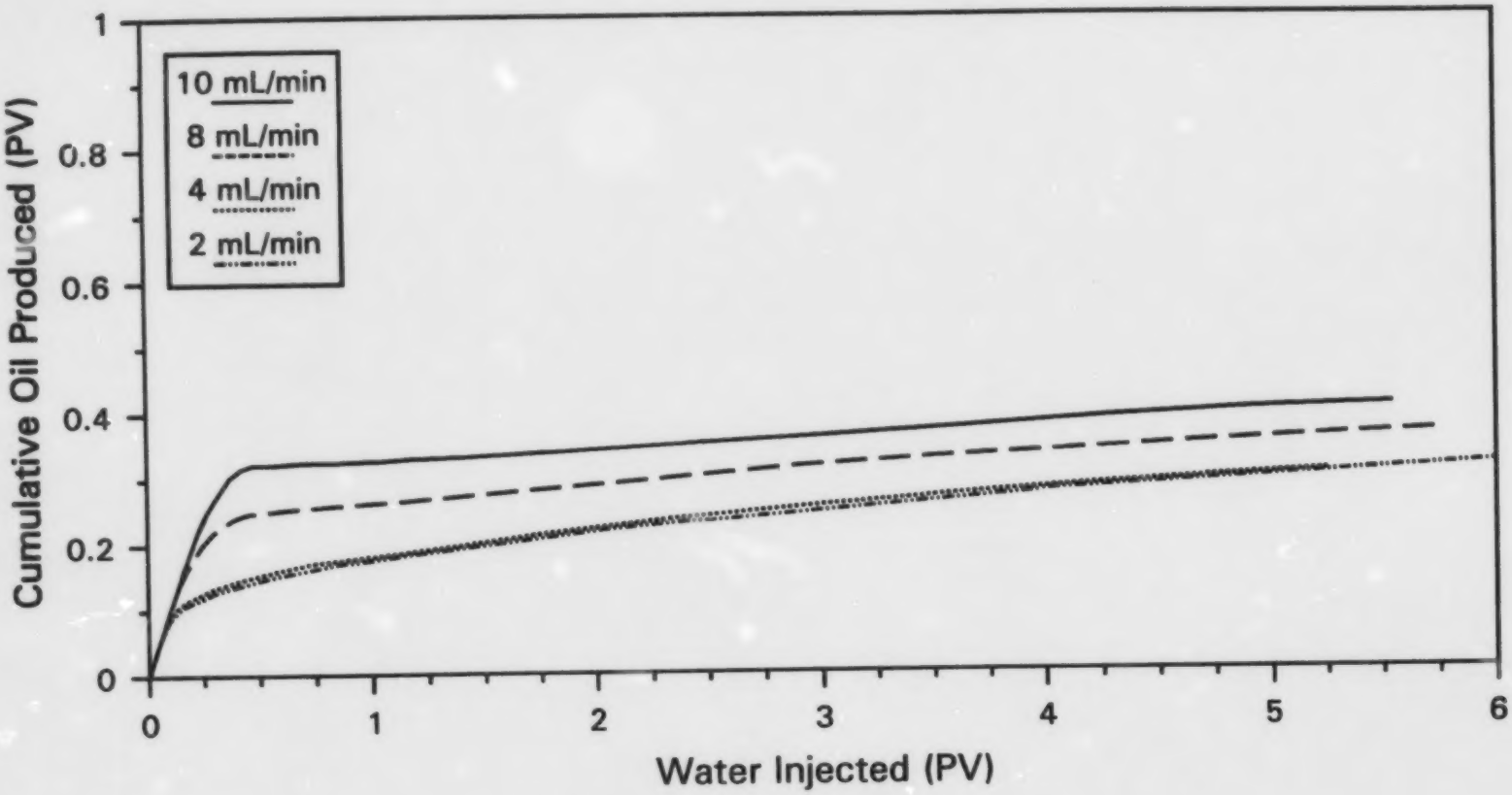


Figure 15: Effect of Displacement Rate on Oil Recovery

(Viscosity Ratio = 419)

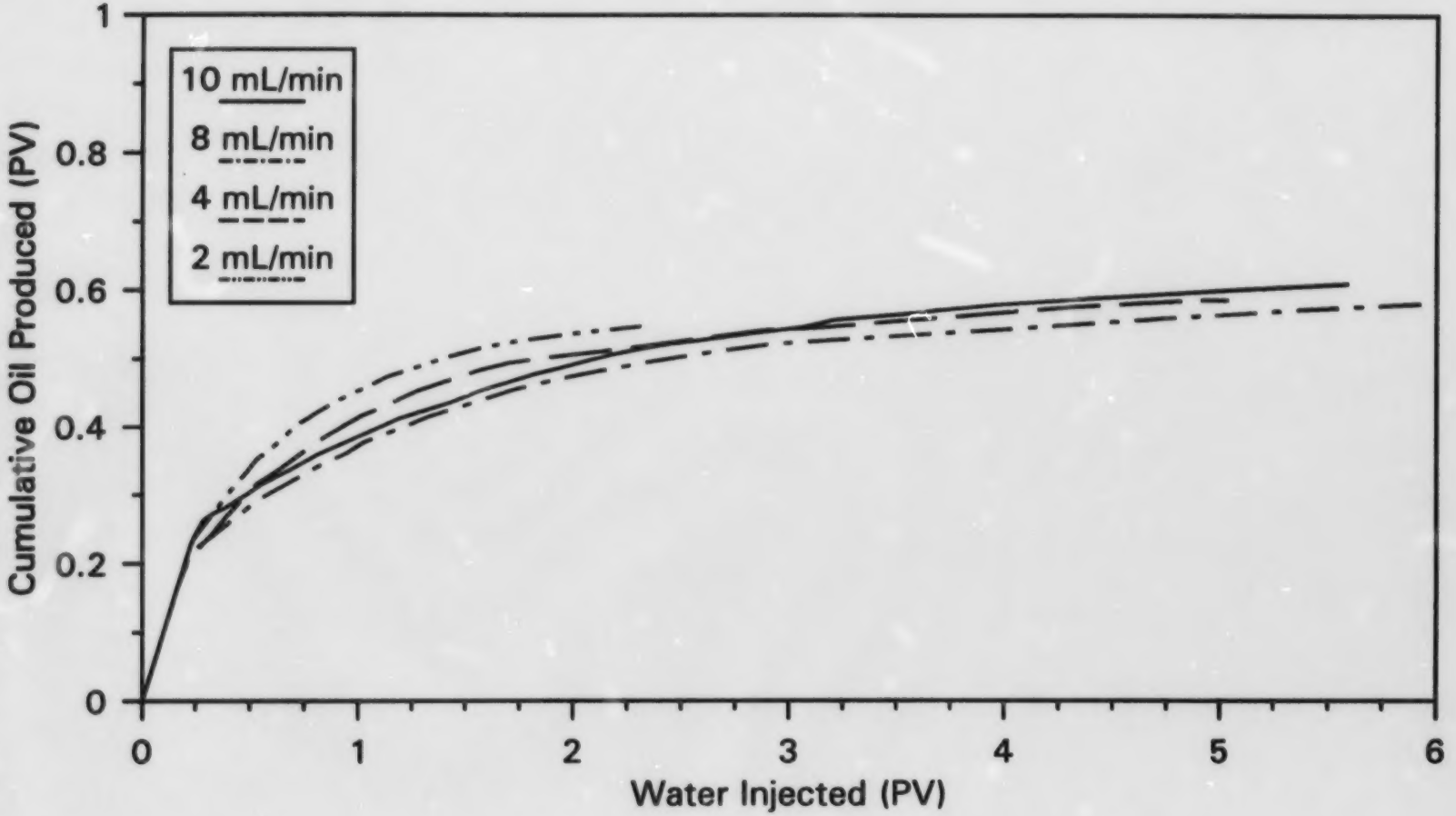


Figure 16: Effect of Displacement Rate on Oil Recovery

(Viscosity Ratio = 42)

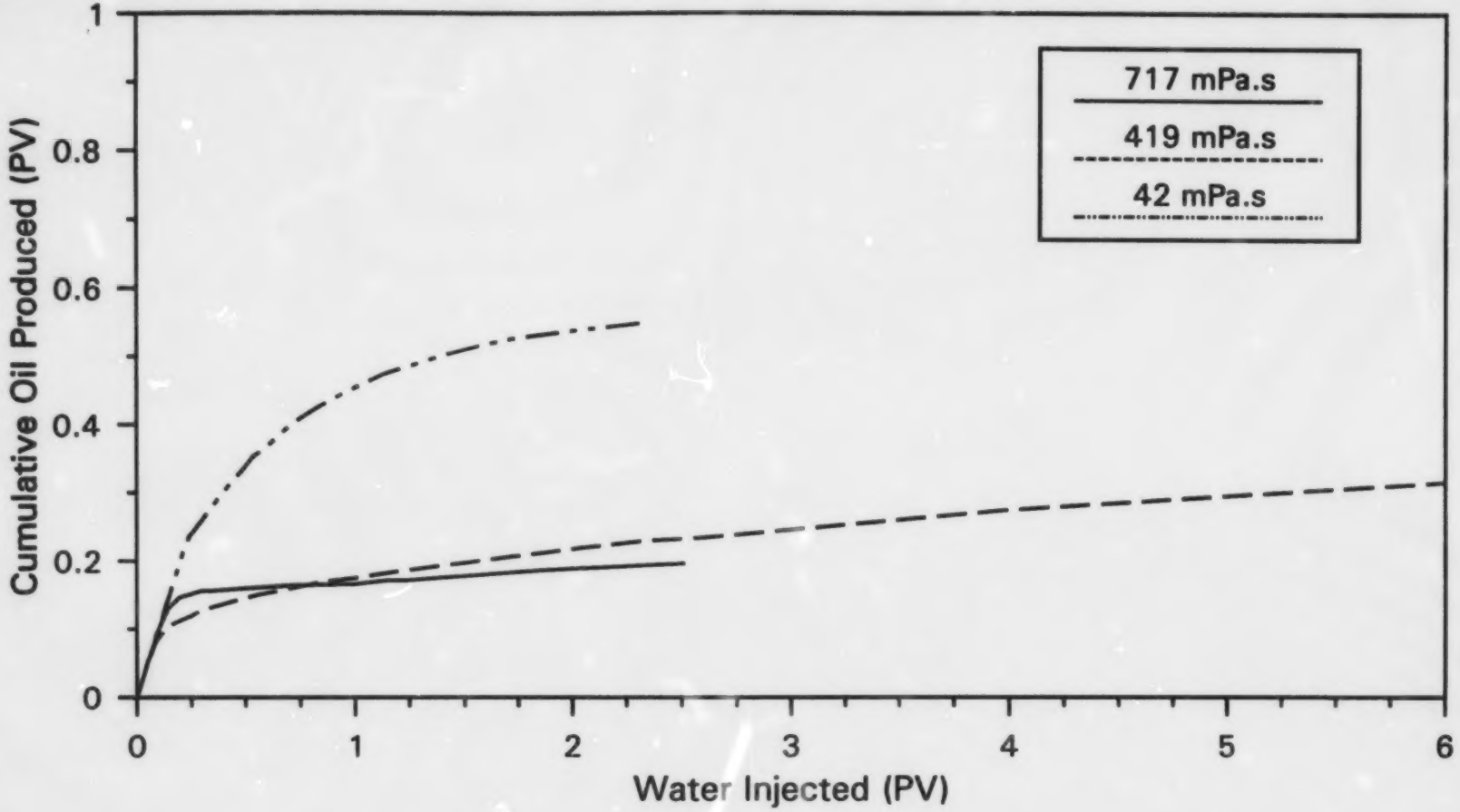


Figure 17: Effect of Oil Viscosity on Oil Recovery

(Flow Rate = 2 mL/min)

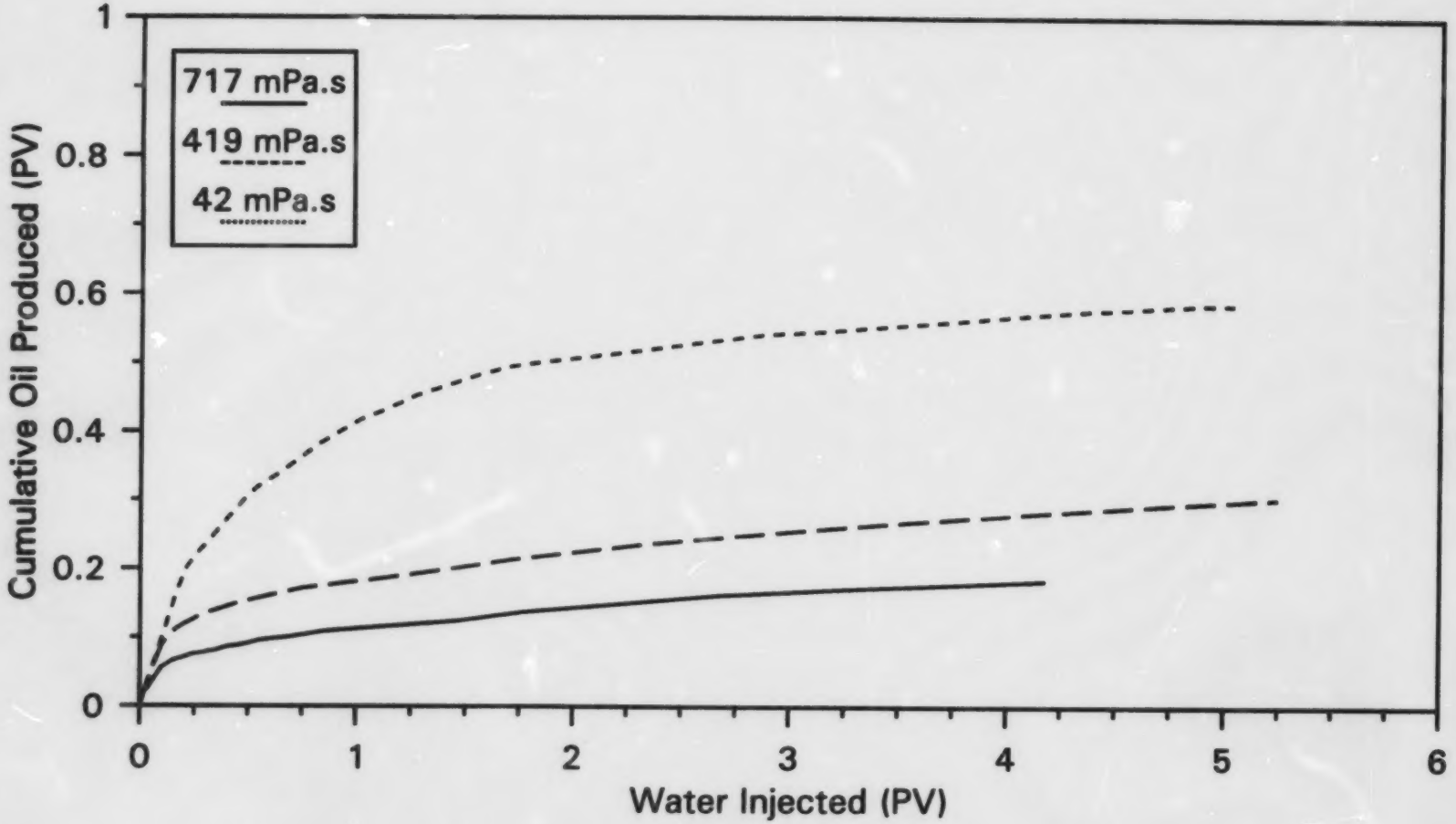


Figure 18: Effect of Oil Viscosity on Oil Recovery

(Flow Rate = 4 mL/min)

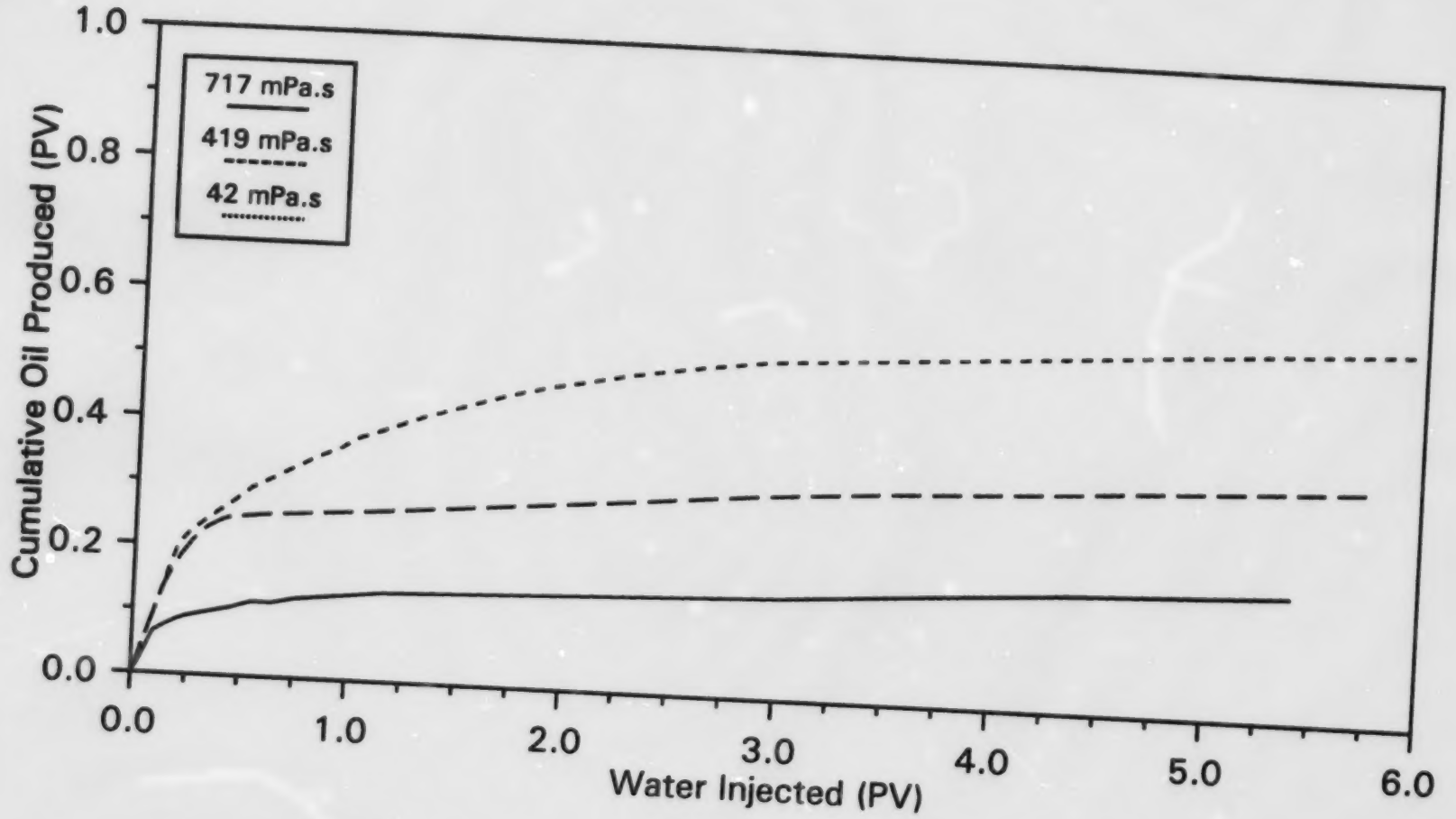


Figure 19: Effect of Oil Viscosity on Oil Recovery

(Flow Rate = 8 mL/min)

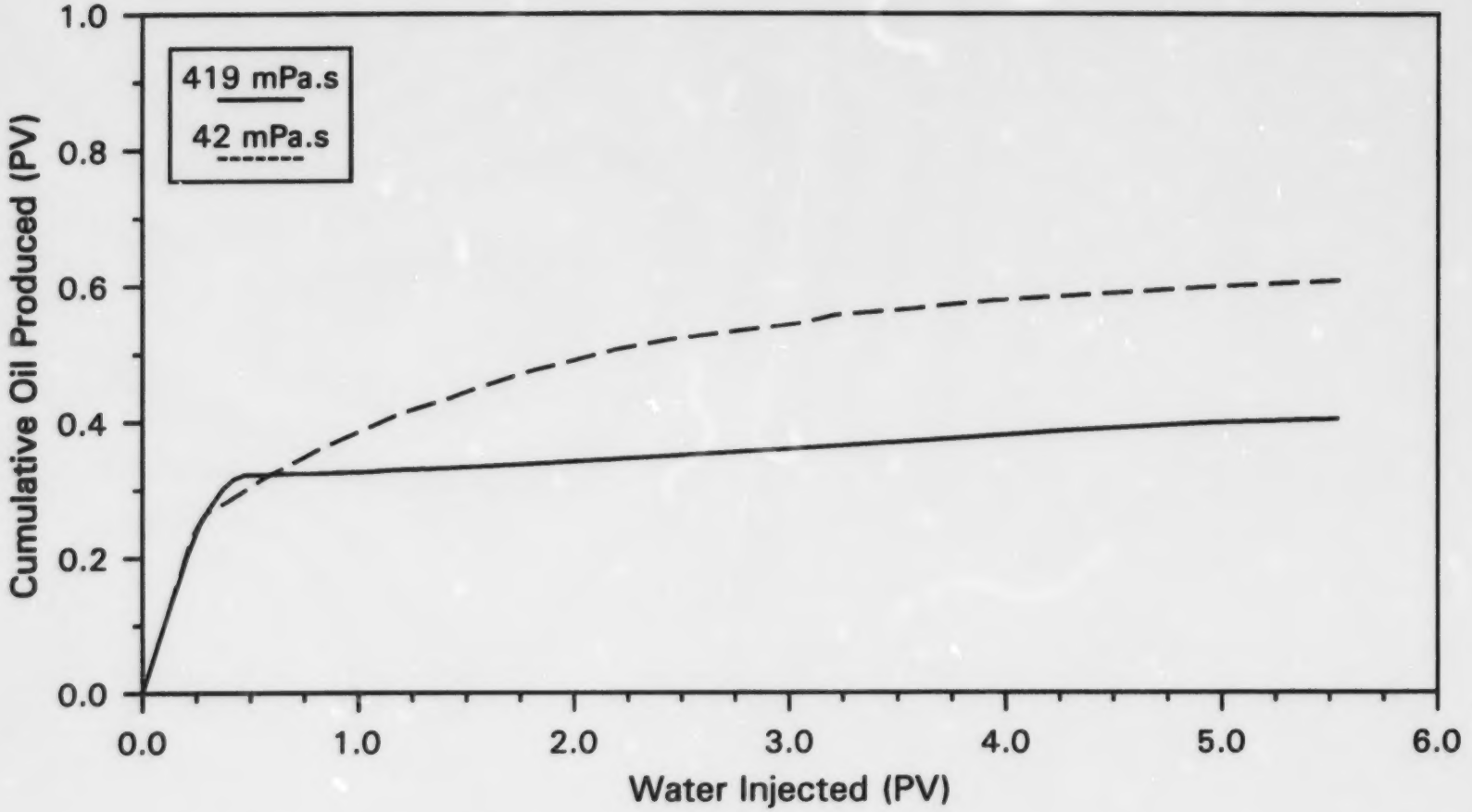


Figure 20: Effect of Oil Viscosity on Oil Recovery
(Flow Rate = 10 mL/min)

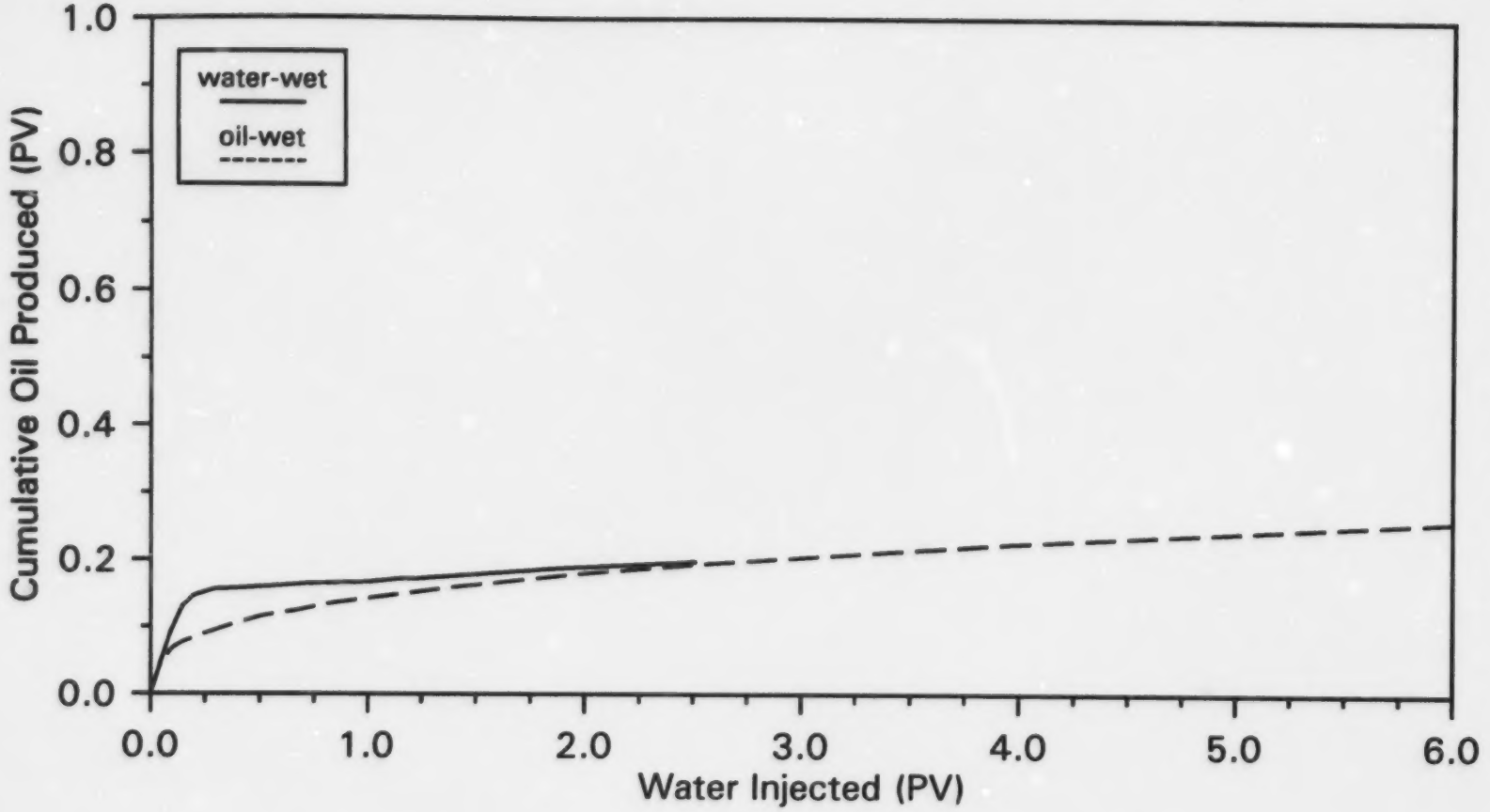


Figure 21: Effect of Initial Wetting Condition on Oil Recovery

(Viscosity Ratio = 717; Flow Rate = 2 mL/min)

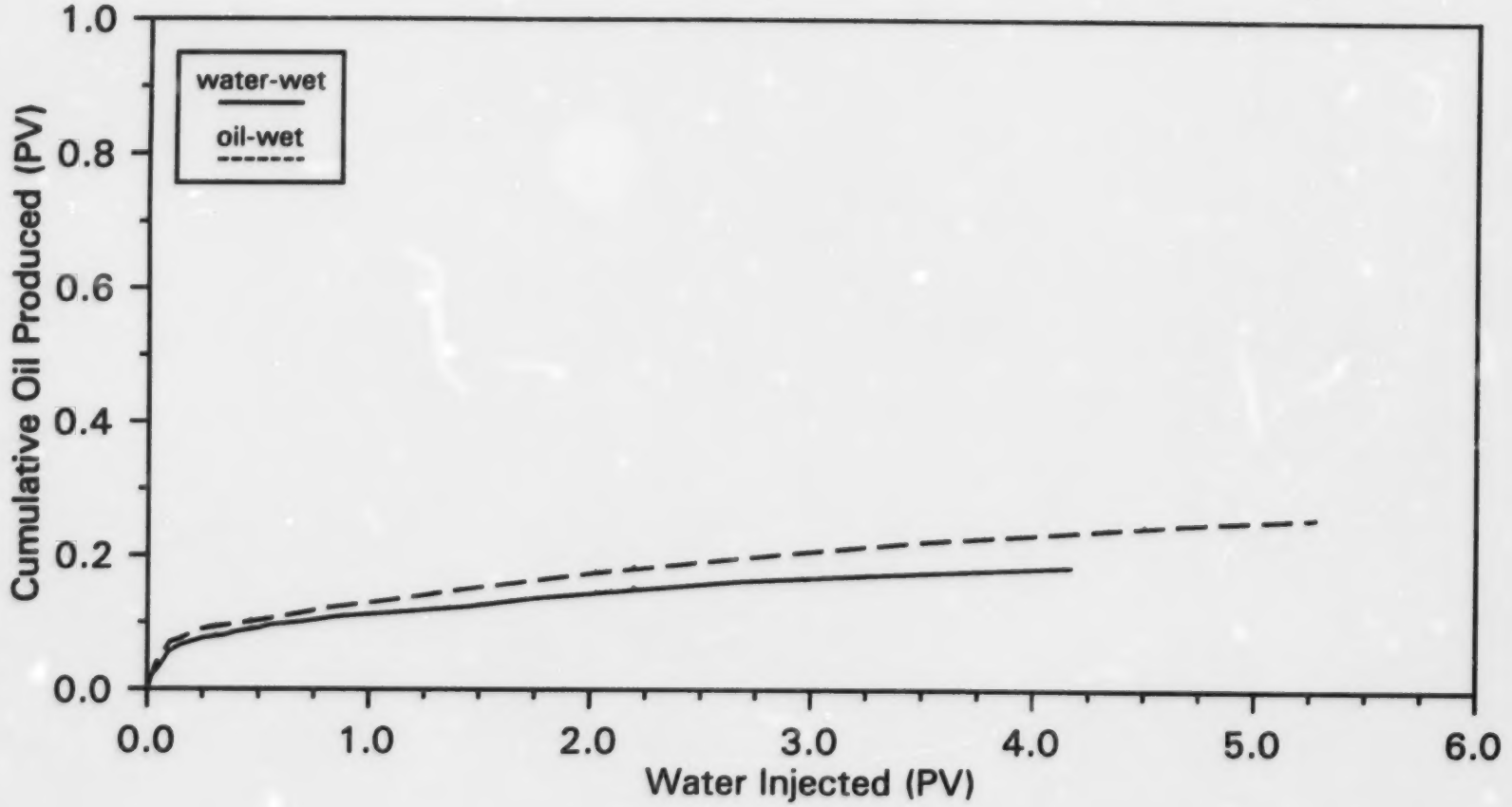


Figure 22: Effect of Initial Wetting Condition on Oil Recovery

(Viscosity Ratio = 717; Flow Rate = 4 mL/min)

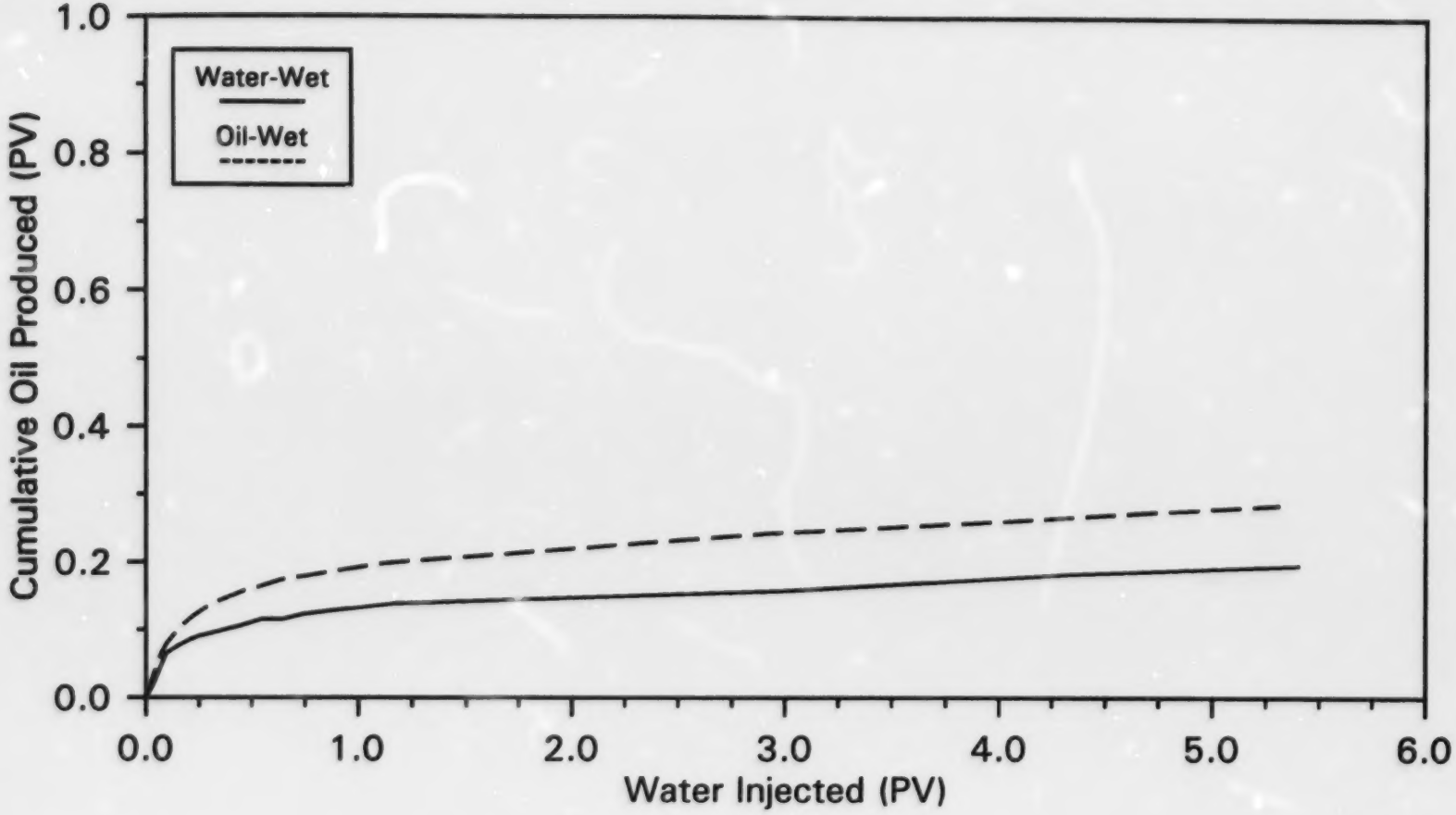


Figure 23: Effect of Initial Wetting Condition on Oil Recovery

(Viscosity Ratio = 717; Flow Rate = 8 mL/min)

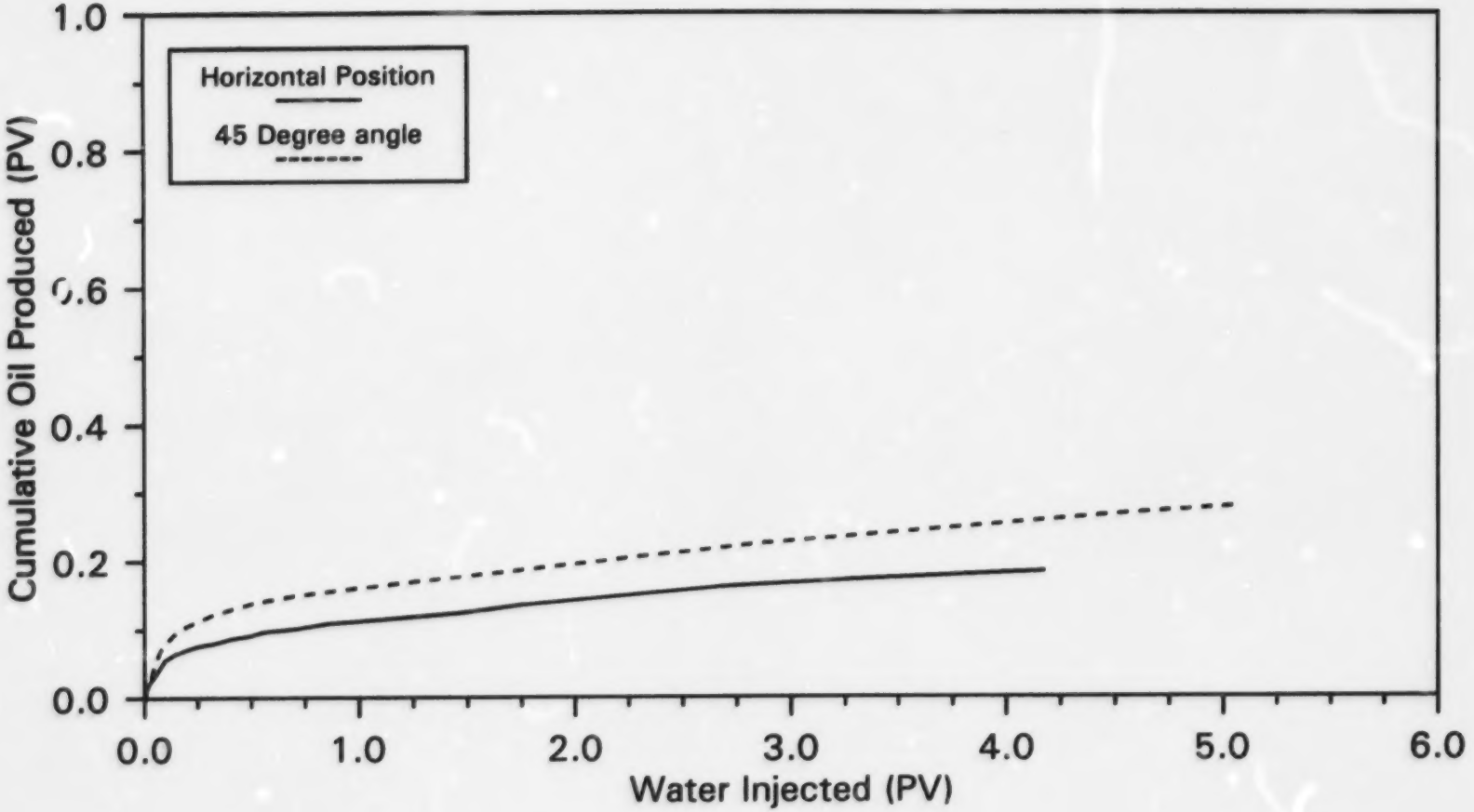


Figure 24: Effect of Gravity on Oil Recovery

(Viscosity Ratio = 717; Flow Rate = 4 mL/min)

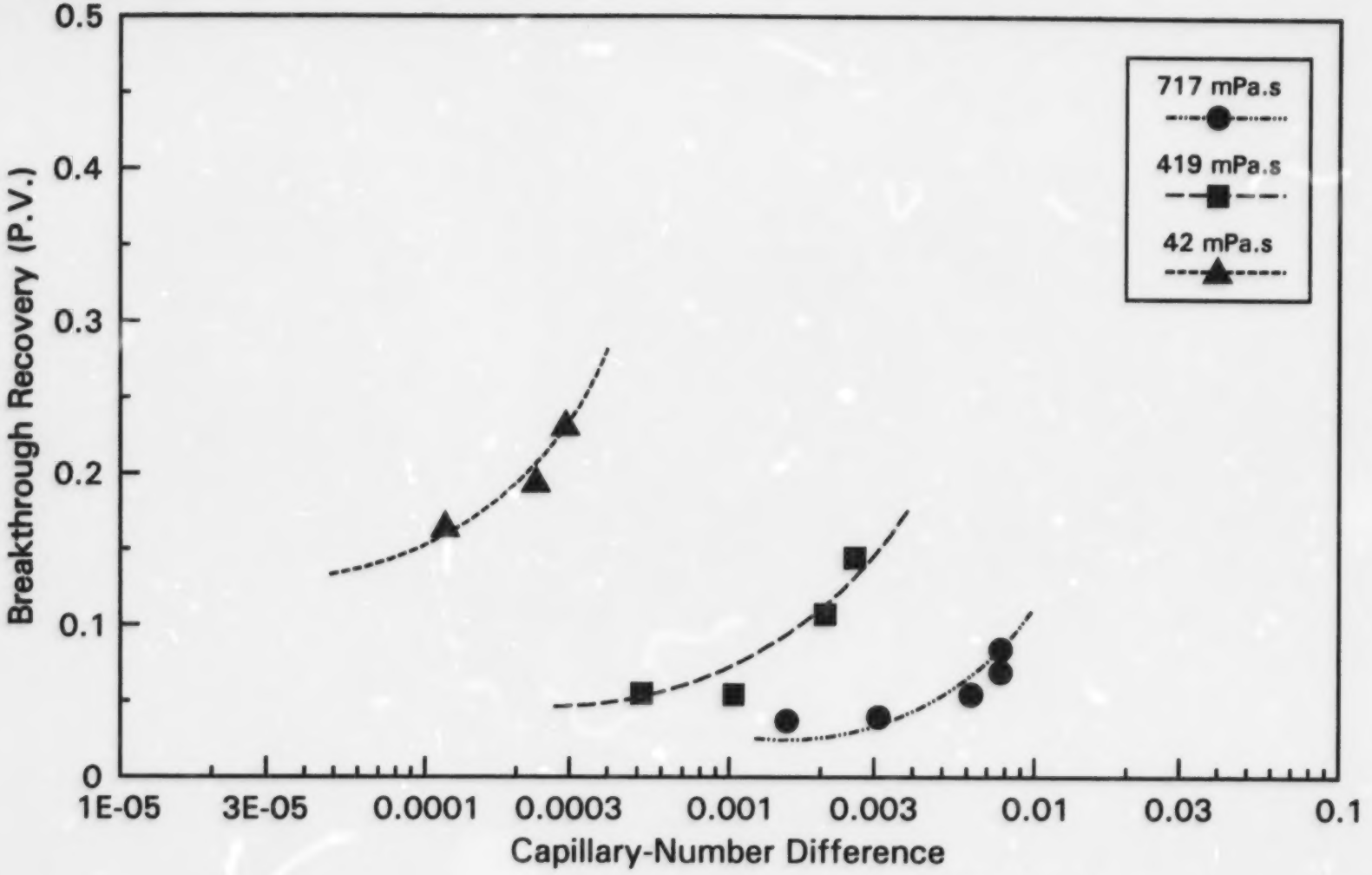


Figure 25: Effect of Capillary Forces on Breakthrough Recovery

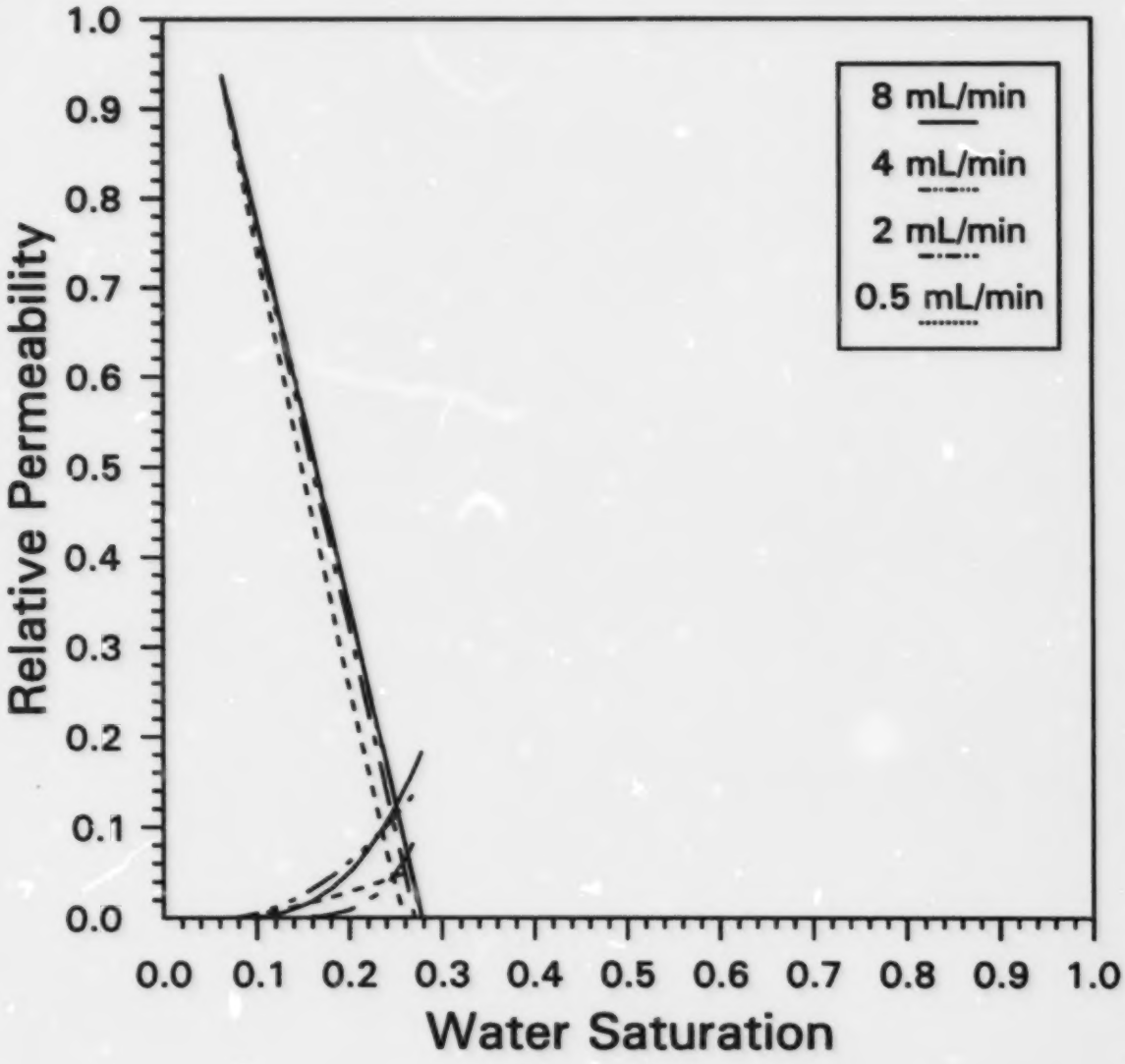


Figure 26: Effect of Displacement Rate on Relative Permeabilities

(Viscosity Ratio = 717; Water-Wet)

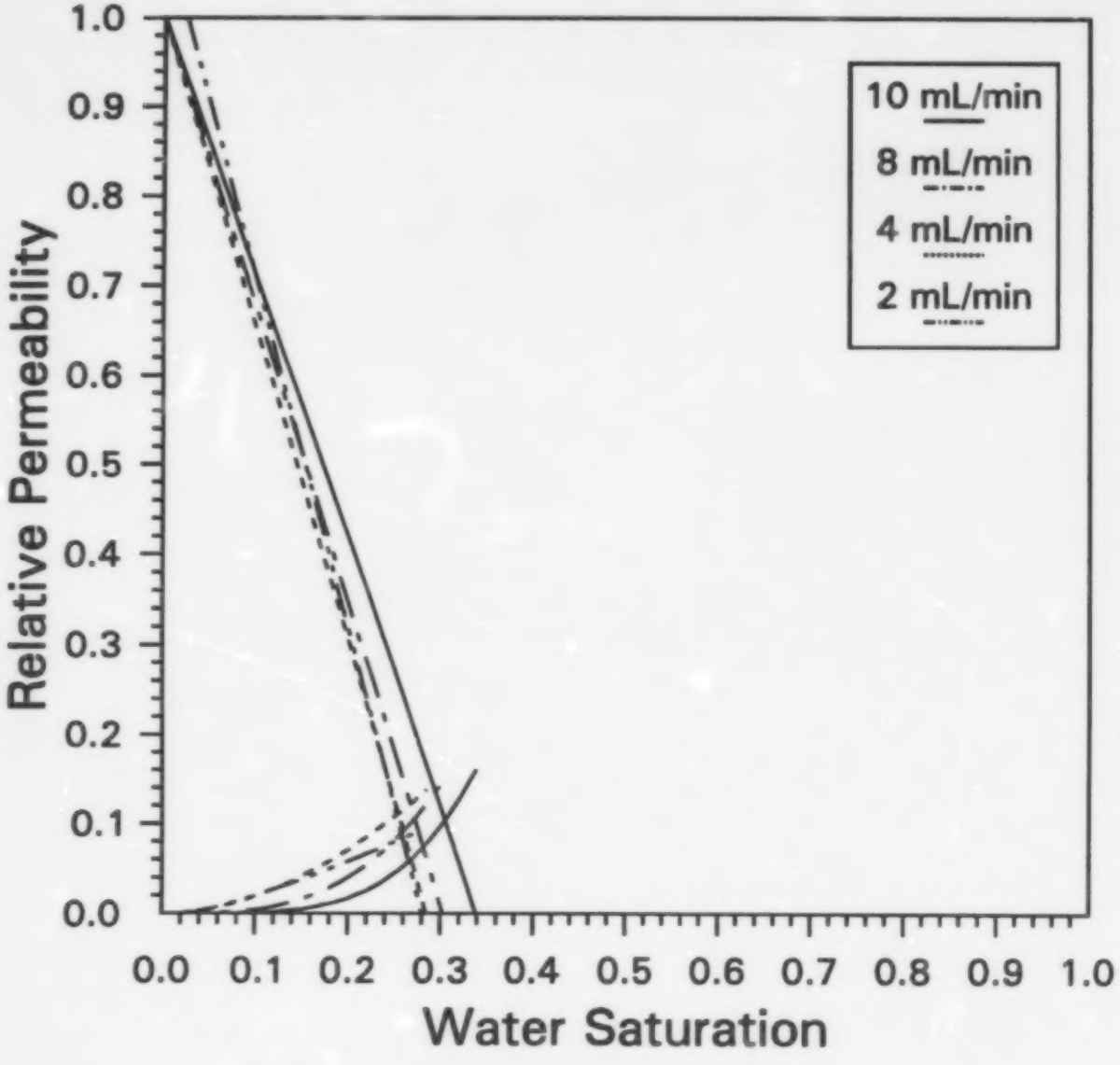


Figure 27: Effect of Displacement Rate on Relative Permeabilities

(Viscosity Ratio = 717; Oil-Wet)

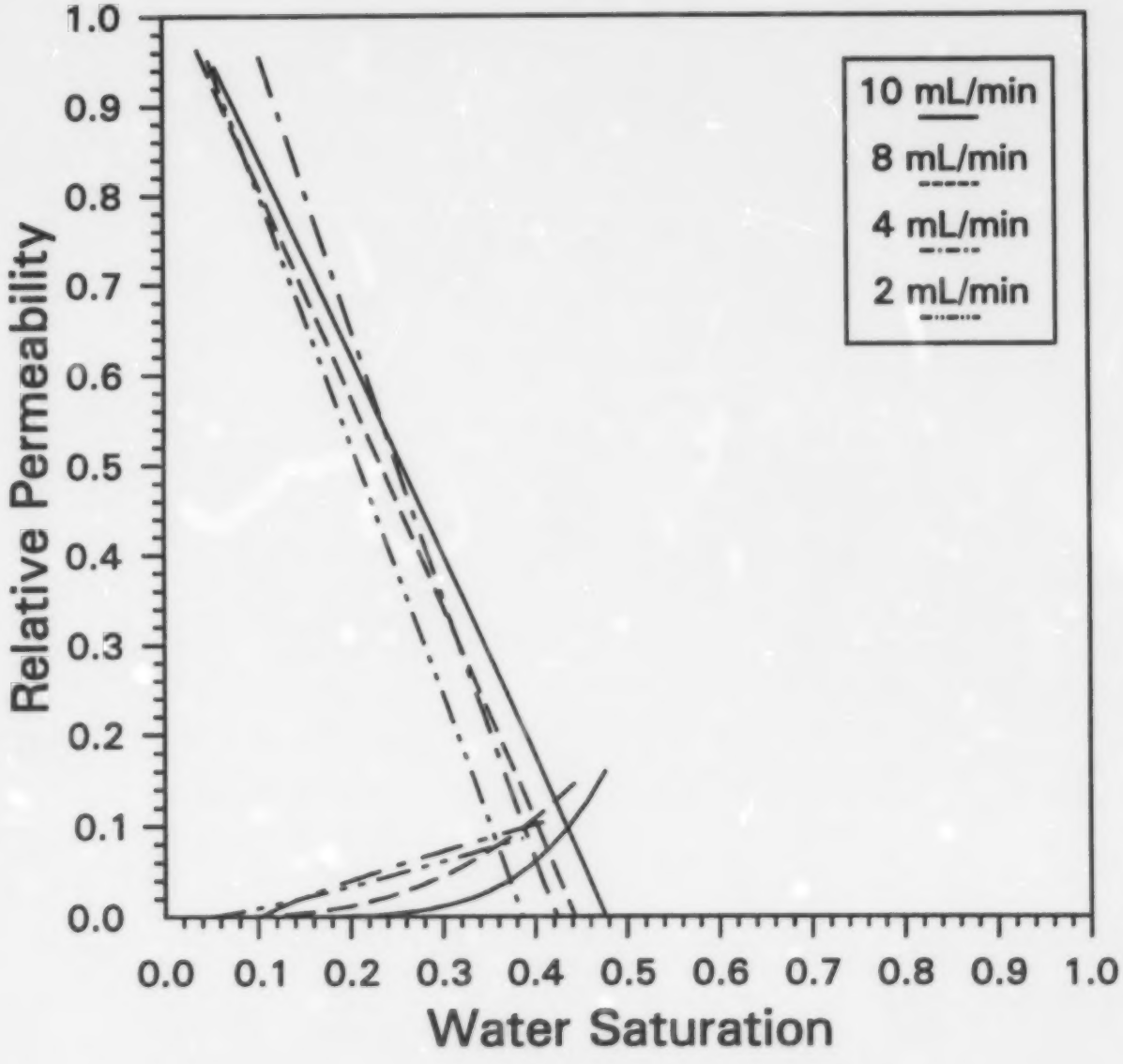


Figure 28: Effect of Displacement Rate on Relative Permeabilities

(Viscosity Ratio = 419)

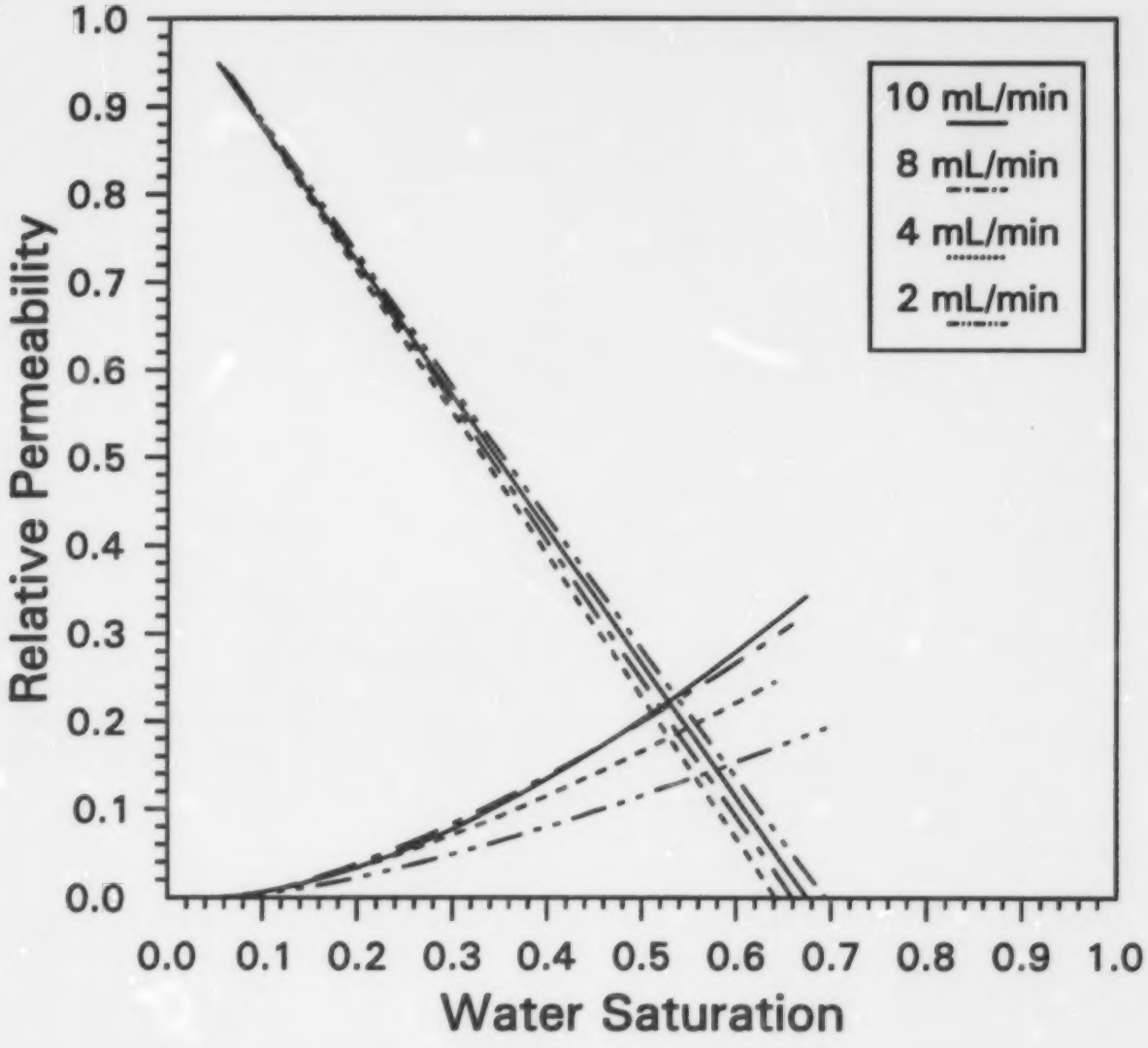


Figure 29: Effect of Displacement Rate on Relative Permeabilities
(Viscosity Ratio = 42)

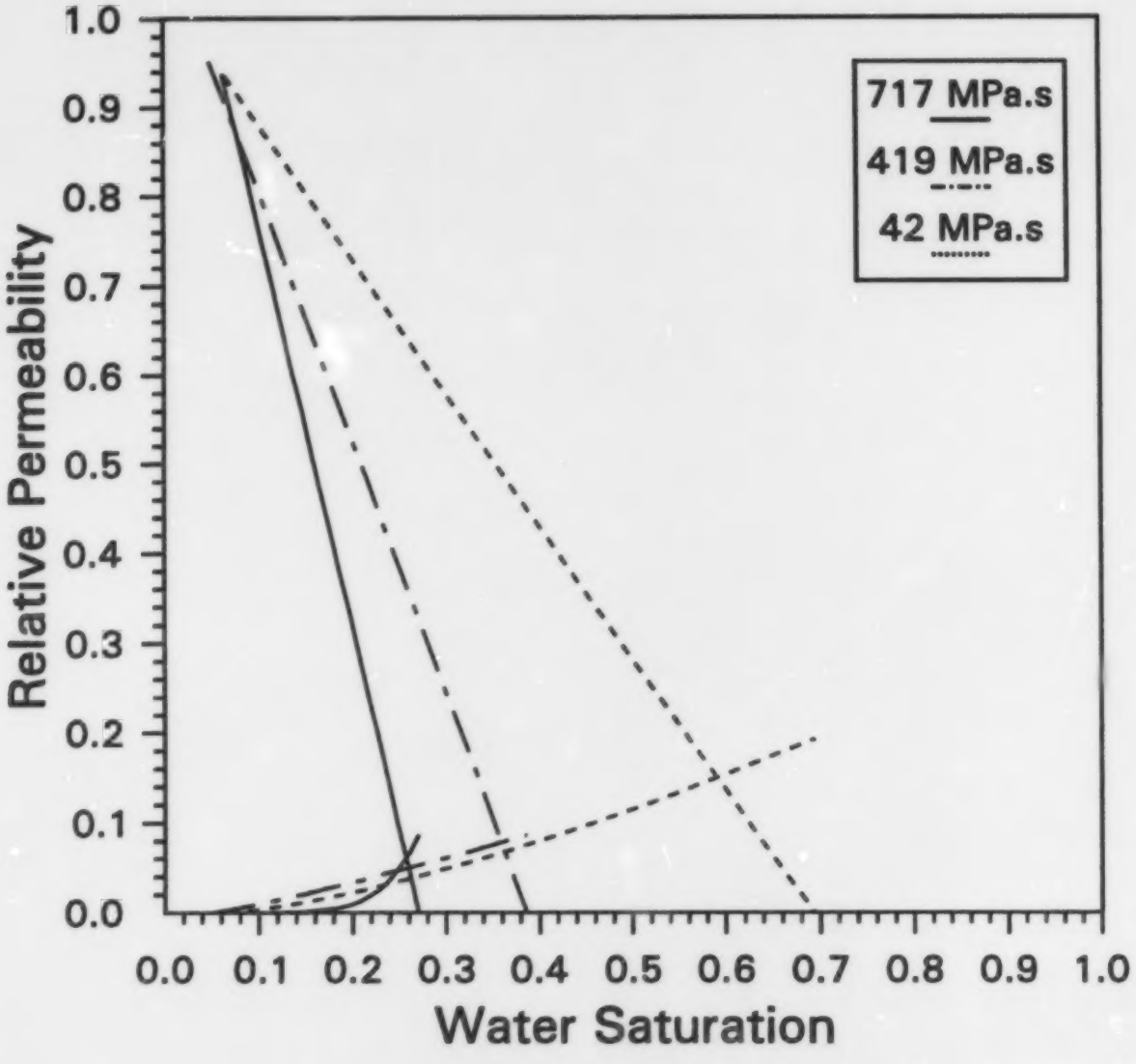


Figure 30: Effect of Oil Viscosity on Relative Permeabilities

(Flow Rate = 2 mL/min)

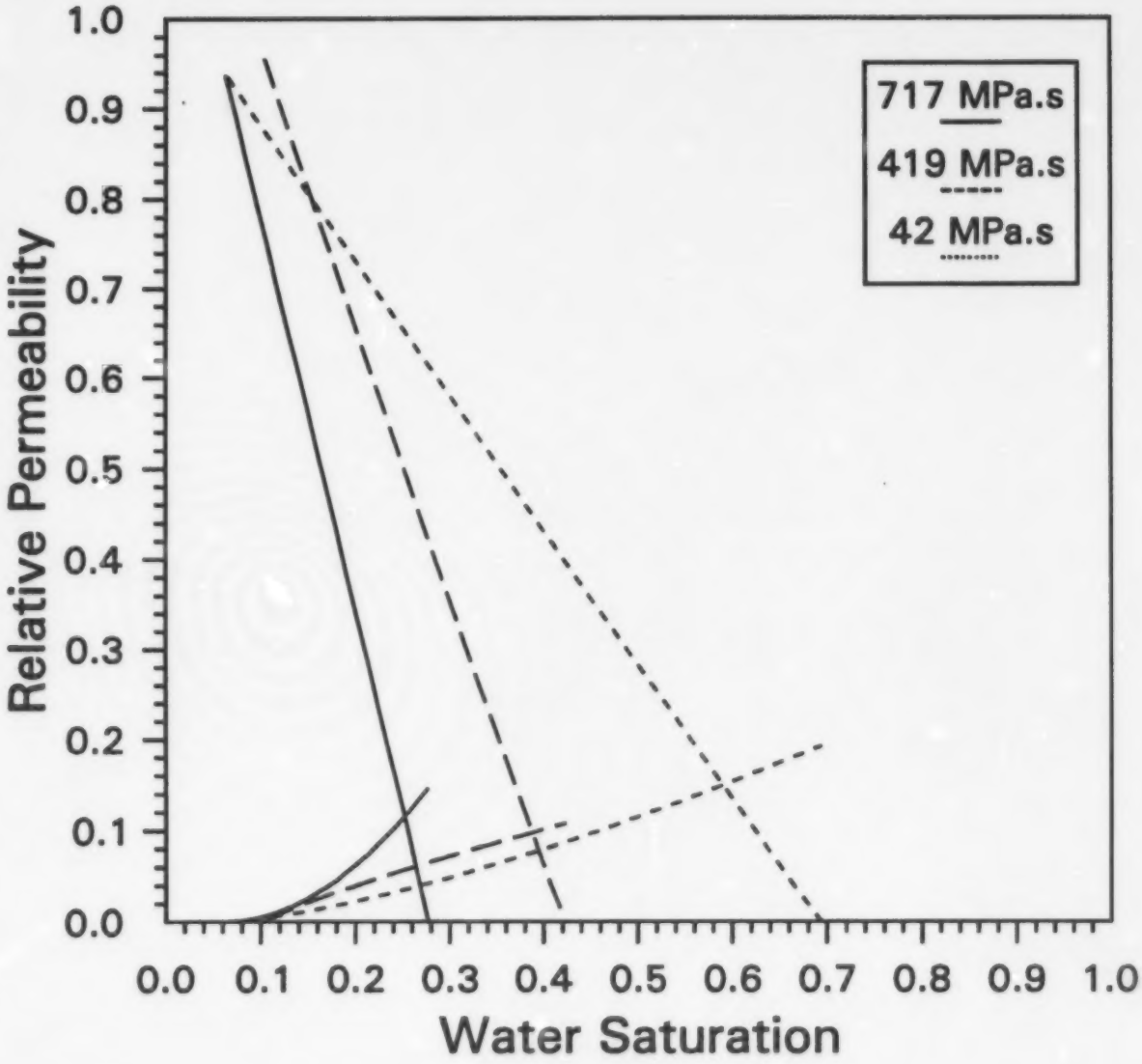


Figure 31: Effect of Oil Viscosity on Relative Permeabilities
(Flow Rate = 4 mL/min)

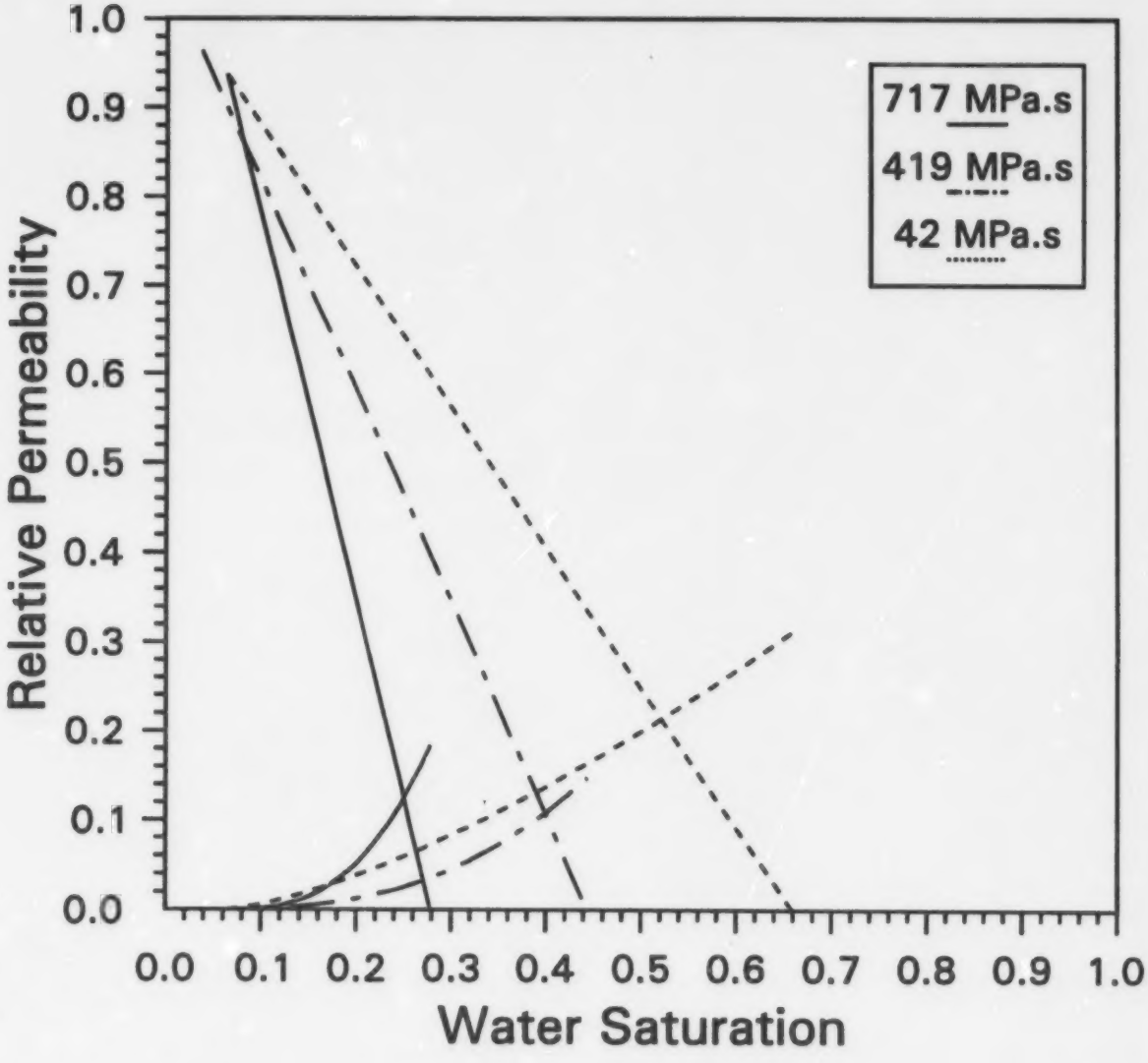


Figure 32: Effect of Oil Viscosity on Relative Permeabilities
(Flow Rate = 8 mL/min)

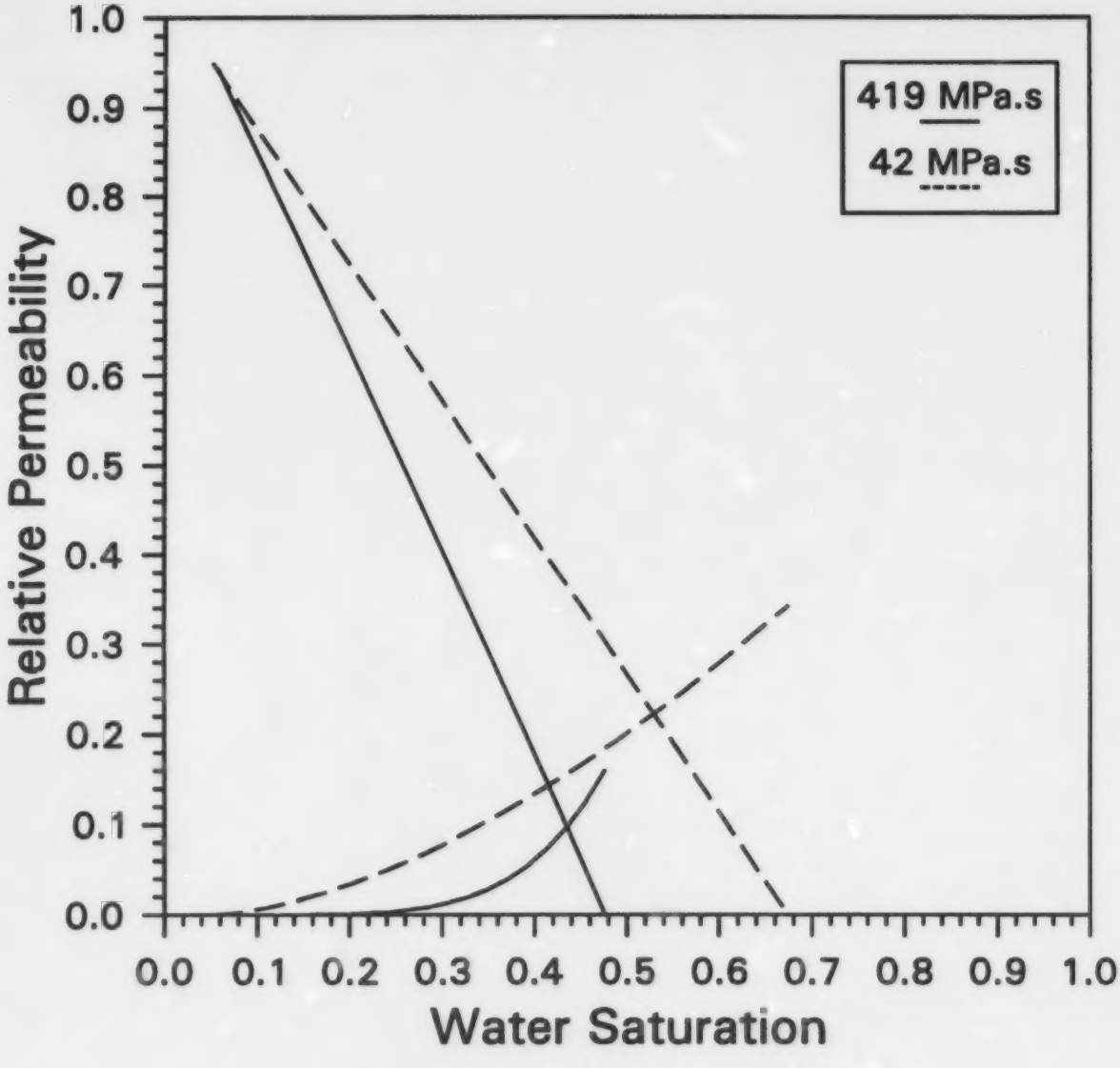


Figure 33: Effect of Oil Viscosity on Relative Permeabilities
(Flow Rat 10 mL/min)

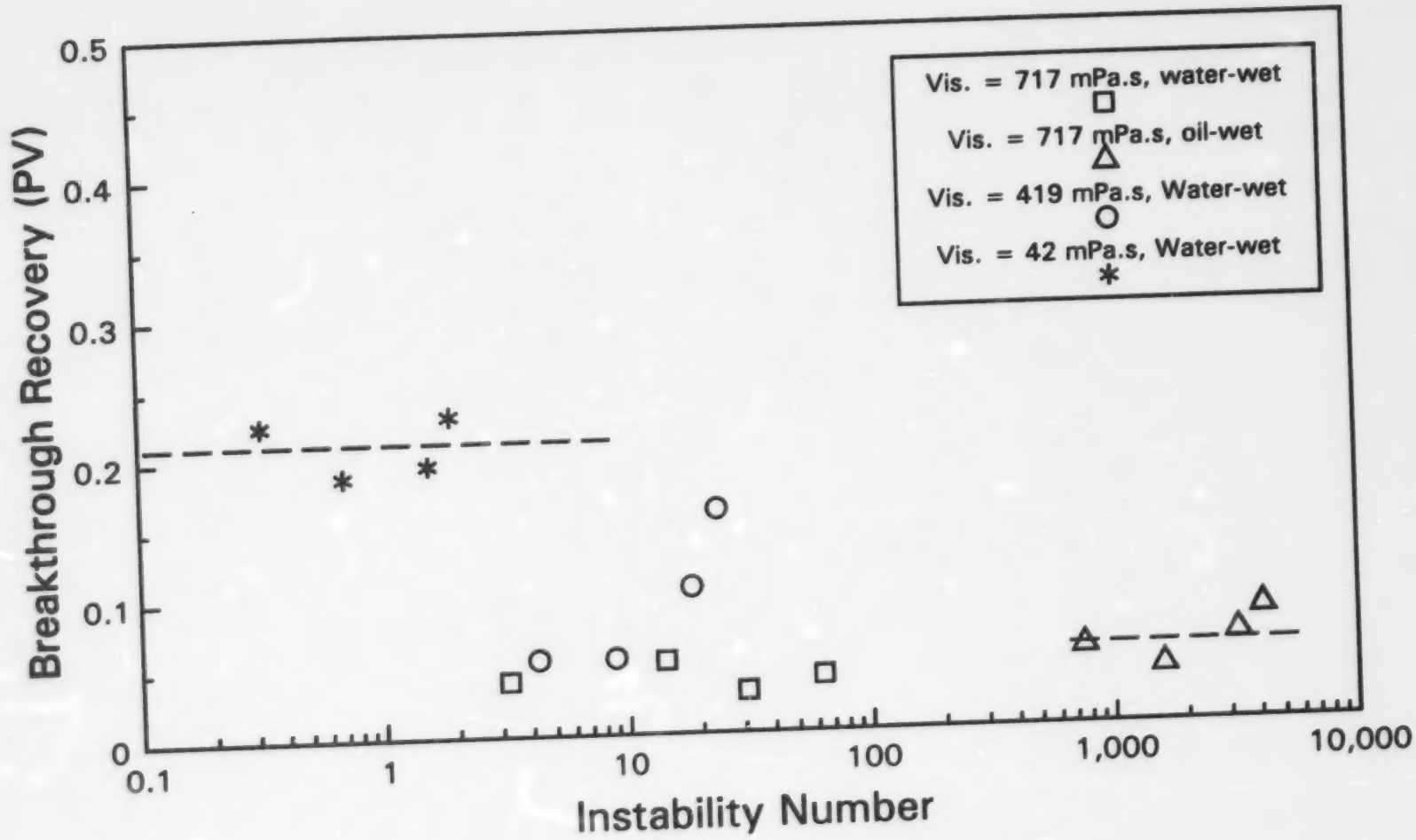


Figure 34: Effect of Instability Number on Breakthrough Recovery

APPENDIX A

RESULTS OF HISTORY MATCHING FOR CALCULATING PSEUDO-RELATIVE PERMEABILITY

The computer program, PRISIM, was used for history matching of the displacement data to obtain the pseudo-relative permeability curves. This appendix provides a listing of the parameters used for different runs as well as a listing of the results obtained. The simulation results for each run are presented in three parts. Part A shows the final values of the adjustable and fixed parameters. Part B compares the simulation results with actual experimental data. Part C lists the calculated values of the pseudo relative permeabilities.

RUN NO. 1 - SUMMARY OF COMPUTER HISTORY MATCH RESULTS

A: Displacement Parameters.

Core Length, cm	31.9
Cross-sectional Area sq. cm	25.7
Core diameter, cm	5.7
Porosity	0.34
Pore Volume, ml	278.2
Absolute Permeability, Darcy	2.7
Viscosity of Displacing Fluid, mPa.s	1
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.75
End Point Rel. Perm. of Displacing Fluid	0.31
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.05
Injection Rate, ml/sec	0.0892
Flood Velocity, m/day	8.8
Initial Pressure Drop, MPa	1.541
c_w	2.4069
c_o	0.975

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		1.540762		0.0500	0.0000
65.0	0.021	0.0321	5.8022	5.40	1.379430	1.10315	0.0709	0.0000
185.0	0.059	0.0913	16.5140	16.20	1.081586	1.11694	0.1094	0.0000
365.0	0.117	0.1802	32.5818	32.70	0.634821	0.59294	0.1671	0.0000
465.6	0.149	0.2299	41.5643		0.385058		0.1994	1.5644
665.0	0.213	0.2619	47.3553	51.20	0.292072	0.26200	0.2202	2.6185
965.0	0.309	0.2964	53.5974	57.20	0.222265	0.19305	0.2427	4.0213
1170.7	0.375	0.3150	56.9643		0.193656		0.2548	4.9158
1265.0	0.406	0.3226	58.3440	62.70	0.183350	0.16547	0.2597	5.3136
1865.0	0.598	0.3624	65.5337	70.20	0.140014	0.11721	0.2856	7.7114
1875.7	0.601	0.3630	65.6433		0.139466		0.2860	7.7525
2465.0	0.790	0.3927	71.0145	75.00	0.115782	0.09653	0.3053	9.9549
2580.7	0.827	0.3978	71.9429		0.112249		0.3086	10.3750
3285.8	1.054	0.4256	76.9616		0.095460		0.3266	12.8677
3485.0	1.117	0.4326	78.2190	82.50	0.091789	0.08963	0.3312	13.5546
3990.8	1.280	0.4488	81.1651		0.083903		0.3418	15.2713
4565.0	1.464	0.4654	84.1598	89.30	0.076792	0.07308	0.3525	17.1801
4695.8	1.506	0.4689	84.7984		0.075381		0.3548	17.6098
5400.9	1.732	0.4867	88.0080		0.068794		0.3663	19.8978
5765.0	1.848	0.4951	89.5323	94.70	0.065934	0.06343	0.3718	21.0639
6105.9	1.958	0.5026	90.8887		0.063522		0.3767	22.1463
6810.9	2.184	0.5171	93.5061		0.059192		0.3861	24.3637
7515.9	2.410	0.5304	95.9070		0.055559		0.3947	26.5547
7745.0	2.483	0.5345	96.6466	99.50	0.054501	0.05378	0.3974	27.2609
8221.0	2.636	0.5426	98.1262		0.052461		0.4027	28.7764
8926.0	2.862	0.5540	100.1849		0.049786		0.4101	30.9860
9425.0	3.022	0.5616	101.5615	103.60	0.048098	0.04826	0.4151	32.4164
9631.0	3.088	0.5647	102.1131		0.047444		0.4170	33.0437
10336.1	3.314	0.5747	103.9237		0.045375		0.4236	35.2643
11041.1	3.540	0.5841	105.6318		0.043531		0.4297	37.2991
11746.1	3.766	0.5931	107.2514		0.041875		0.4355	39.4702
12065.0	3.868	0.5970	107.9554	109.70	0.041180	0.04137	0.4380	40.4459
12451.2	3.992	0.6016	108.7868		0.040379		0.4410	41.5852
13156.2	4.218	0.6097	110.2509		0.039019		0.4463	43.5540
13861.2	4.444	0.6174	111.6488		0.037776		0.4513	45.7768
13865.0	4.446	0.6175	111.6561	115.20	0.037770	0.03861	0.4514	45.7883
14566.3	4.670	0.6248	112.9844		0.036636		0.4561	47.8663
15271.3	4.896	0.6319	114.2664		0.035584		0.4607	49.8325
15976.3	5.123	0.6387	115.4982		0.034611		0.4652	52.0262
16681.4	5.349	0.6453	116.6812		0.033706		0.4694	54.1425
16865.0	5.407	0.6469	116.9821	117.90	0.033483	0.03447	0.4705	54.6761
17386.4	5.575	0.6516	117.8214		0.032867		0.4735	56.1528
18091.4	5.801	0.6577	118.9231		0.032081		0.4775	58.2152
18365.0	5.888	0.6600	119.3400	120.60	0.031790	0.03309	0.4790	59.0729
18796.5	6.027	0.6635	119.9859		0.031345		0.4813	60.3965

19501.5	6.253	0.6692	121.0130		0.030655		0.4850	62.4842
20206.5	6.479	0.6747	122.0081		0.030005		0.4886	64.4838
20765.0	6.658	0.6790	122.7755	122.00	0.029516	0.03103	0.4913	66.1083
20911.6	6.705	0.6801	122.9738		0.029391		0.4920	66.5740
21616.6	6.931	0.6852	123.9093		0.028812		0.4954	68.7652
22321.6	7.157	0.6902	124.8170		0.028264		0.4987	70.8769
23026.6	7.383	0.6951	125.6993		0.027744		0.5018	72.9127
23731.7	7.609	0.6999	126.5586		0.027250		0.5049	74.9088
23885.0	7.658	0.7009	126.7424	125.40	0.027146	0.02896	0.5056	75.4028
24436.7	7.835	0.7045	127.3946		0.026781		0.5079	77.1521
25141.7	8.061	0.7090	128.2077		0.026333		0.5108	79.3260
25846.8	8.287	0.7134	129.0000		0.025907		0.5137	81.4332
26551.8	8.513	0.7177	129.7729		0.025499		0.5165	83.4766
27256.8	8.739	0.7218	130.5281		0.025109		0.5192	85.5229
27961.9	8.965	0.7259	131.2649		0.024736		0.5218	87.7890
28666.9	9.192	0.7299	131.9839		0.024378		0.5244	89.9961
29371.9	9.418	0.7338	132.6862		0.024036		0.5269	92.1457
30077.0	9.644	0.7376	133.3731		0.023706		0.5294	94.2401
30782.0	9.870	0.7413	134.0457		0.023389		0.5318	96.2812
31487.0	10.096	0.7449	134.7043		0.023085		0.5342	98.5161
31985.0	10.255	0.7474	135.1606	132.90	0.022876	0.02551	0.5358	100.1303
32192.1	10.322	0.7485	135.3483		0.022791		0.5365	100.7942
32897.1	10.548	0.7520	135.9786		0.022509		0.5388	103.0222
33602.1	10.774	0.7554	136.5961		0.022236		0.5410	105.2024
34307.1	11.000	0.7587	137.2014		0.021973		0.5432	107.3345

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_{rl}	k_{rp}
0.050	0.0000E+00	0.1000E+01
0.082	0.3010E-03	0.9512E+00
0.115	0.1596E-02	0.9024E+00
0.147	0.4236E-02	0.8535E+00
0.180	0.8466E-02	0.8045E+00
0.212	0.1449E-01	0.7554E+00
0.245	0.2247E-01	0.7063E+00
0.277	0.3256E-01	0.6570E+00
0.310	0.4490E-01	0.6077E+00
0.342	0.5962E-01	0.5583E+00
0.375	0.7682E-01	0.5087E+00
0.407	0.9663E-01	0.4591E+00
0.440	0.1191E+00	0.4093E+00
0.472	0.1445E+00	0.3593E+00
0.505	0.1727E+00	0.3092E+00
0.538	0.2039E+00	0.2588E+00
0.570	0.2381E+00	0.2082E+00
0.603	0.2755E+00	0.1573E+00
0.635	0.3162E+00	0.1059E+00
0.668	0.3601E+00	0.5389E-01
0.700	0.4074E+00	0.0000E+00

RUN NO. 2 - SUMMARY OF COMPUTER HISTORY MATCH

A: Displacement Parameters.

Core Length, cm	11.8
Cross-sectional Area sq. cm	25.7
Core diameter, cm	5.7
Porosity	0.343
Pore Volume, ml	103.82
Absolute Permeability, Darcy	3.41
Viscosity of Displacing Fluid, mPa.s	1
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.82
End Point Rel. Perm. of Displacing Fluid	0.29
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.05
Injection Rate, ml/sec	0.0892
Flood Velocity, m/day	8.8
Initial Pressure Drop, MPa	0.6604
c_w	3.3
c_o	0.98

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		0.549582		0.0500	0.0000
75.0	0.064	0.0992	6.6911	6.50	0.436163	0.38610	0.1145	0.0000
180.0	0.155	0.2380	16.0587	12.70	0.277375	0.24821	0.2047	0.0000
288.5	0.248	0.3815	25.7429		0.113220		0.2980	2.6767
360.0	0.309	0.4044	27.2881	24.20	0.094918	0.08963	0.3129	3.6070
549.3	0.472	0.4484	30.2589		0.068782		0.3415	5.8976
600.0	0.516	0.4578	30.8897	30.00	0.064414	0.05516	0.3475	6.4864
810.0	0.696	0.4900	33.0664		0.051733		0.3685	8.8512
1070.7	0.920	0.5208	35.1461		0.042370		0.3885	11.6787
1200.0	1.031	0.5337	36.0129	39.30	0.039091	0.02620	0.3969	13.0514
1331.4	1.144	0.5455	36.8113		0.036343		0.4046	14.4290
1592.1	1.368	0.5662	38.2058		0.032093		0.4180	17.1279
1800.0	1.547	0.5806	39.1778	42.80	0.029489	0.02068	0.4274	19.2520
1852.8	1.592	0.5840	39.4085		0.028910		0.4296	19.7878
2113.5	1.816	0.5997	40.4674		0.026425		0.4398	22.4216
2374.2	2.040	0.6137	41.4144		0.024422		0.4489	25.0346
2634.9	2.264	0.6264	42.2716		0.022768		0.4572	27.6337
2895.6	2.488	0.6380	43.0549		0.021375		0.4647	30.2209
3000.0	2.578	0.6424	43.3506	44.00	0.020877	0.01586	0.4676	31.2553
3156.3	2.712	0.6487	43.7763		0.020184		0.4717	32.8009
3417.0	2.936	0.6586	44.4451		0.019152		0.4781	35.3758
3677.7	3.160	0.6679	45.0686		0.018247		0.4841	37.9488
3900.0	3.351	0.6753	45.5688	46.20	0.017559	0.01379	0.4889	40.1402
3938.4	3.384	0.6765	45.6526		0.017447		0.4897	40.5200
4199.1	3.608	0.6847	46.2018		0.016733		0.4950	43.0912
4459.8	3.832	0.6924	46.7202		0.016092		0.5000	45.6648
4720.5	4.056	0.6996	47.2105		0.015512		0.5048	48.3321
4800.0	4.124	0.7018	47.3548	48.50	0.015346	0.01241	0.5061	49.1207
4981.2	4.280	0.7065	47.6758		0.014985		0.5092	50.8664
5241.9	4.504	0.7131	48.1191		0.014504		0.5135	53.4899
5502.7	4.728	0.7193	48.5416		0.014062		0.5176	56.0854
5763.4	4.952	0.7253	48.9459		0.013654		0.5215	58.6290
6024.1	5.176	0.7311	49.3329		0.013277		0.5252	61.3121
6284.8	5.400	0.7366	49.7042		0.012927		0.5288	63.8748
6545.5	5.624	0.7419	50.0613		0.012601		0.5322	66.5031
6600.0	5.671	0.7429	50.1343	53.60	0.012536	0.01103	0.5329	67.0731
6806.2	5.848	0.7470	50.4047		0.012297		0.5355	69.1852
7066.9	6.072	0.7519	50.7356		0.012012		0.5387	71.7625
7327.6	6.296	0.7566	51.0552		0.011745		0.5418	74.4198
7588.3	6.520	0.7612	51.3636		0.011493		0.5448	77.1419
7849.0	6.744	0.7656	51.6618		0.011256		0.5476	79.7708
8109.7	6.968	0.7699	51.9507		0.011032		0.5504	82.3849
8370.4	7.192	0.7740	52.2304		0.010821		0.5531	85.1793
8400.0	7.217	0.7745	52.2617	54.80	0.010797	0.00965	0.5534	85.4912
8631.1	7.416	0.7780	52.5016		0.010620		0.5557	87.8902

8891.8	7.640	0.7819	52.7649		0.010429		0.5583	90.5212
9152.5	7.864	0.7857	53.0208		0.010248		0.5607	93.2678
9413.2	8.088	0.7894	53.2693		0.010075		0.5631	96.0864
9673.9	8.312	0.7930	53.5109		0.009911		0.5654	98.8323
9934.6	8.536	0.7965	53.7462		0.009754		0.5677	101.5082
10195.3	8.760	0.7999	53.9755		0.009603		0.5699	104.3012
10200.0	8.764	0.7999	53.9795	56.90	0.009601	0.00896	0.5700	104.3528
10456.0	8.984	0.8032	54.1988		0.009460		0.5721	107.1836
10716.8	9.208	0.8064	54.4164		0.009322		0.5742	110.0023
10977.5	9.432	0.8096	54.6287		0.009190		0.5762	112.7577
11238.2	9.656	0.8126	54.8362		0.009063		0.5782	115.4915
11498.9	9.880	0.8156	55.0387		0.008942		0.5802	118.4712
11759.6	10.104	0.8186	55.2364		0.008825		0.5821	121.3935
12000.0	10.311	0.8212	55.4147	57.10	0.008721	0.00965	0.5838	124.0389
12020.3	10.328	0.8214	55.4296		0.008712		0.5839	124.2592
12281.0	10.552	0.8242	55.6185		0.008604		0.5857	127.0713
12541.7	10.776	0.8270	55.8035		0.008499		0.5875	129.9135
12802.4	11.000	0.8296	55.9845		0.008398		0.5893	132.9669

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_{rl}	k_{rp}
0.050	0.0000E+00	0.1000E+01
0.082	0.1811E-04	0.9512E+00
0.115	0.1785E-03	0.9023E+00
0.147	0.6807E-03	0.8533E+00
0.180	0.1760E-02	0.8043E+00
0.212	0.3676E-02	0.7552E+00
0.245	0.6710E-02	0.7060E+00
0.277	0.1116E-01	0.6568E+00
0.310	0.1735E-01	0.6074E+00
0.342	0.2559E-01	0.5580E+00
0.375	0.3623E-01	0.5084E+00
0.407	0.4963E-01	0.4587E+00
0.440	0.6614E-01	0.4089E+00
0.472	0.8615E-01	0.3590E+00
0.505	0.1100E+00	0.3088E+00
0.538	0.1382E+00	0.2585E+00
0.570	0.1710E+00	0.2079E+00
0.603	0.2089E+00	0.1570E+00
0.635	0.2522E+00	0.1057E+00
0.668	0.3015E+00	0.5375E-01
0.700	0.3571E+00	0.0000E+00

RUN NO. 3 - SUMMARY OF COMPUTER HISTORY MATCH RESULTS

A: Displacement Parameters.

Core Length, cm	9.8
Cross-sectional Area sq. cm	66.6
Core diameter, cm	9.2
Porosity	0.359
Pore Volume, ml	234.31
Absolute Permeability, Darcy	2.77
Viscosity of Displacing Fluid, mPa.s	1
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.81
End Point Rel. Perm. of Displacing Fluid	0.36
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.05
Injection Rate, ml/sec	0.2225
Flood Velocity, m/day	8.0
Initial Pressure Drop, MPa	0.5457
ϵ_w	3.0
ϵ_o	1.4

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		0.545671		0.0500	0.0000
70.0	0.066	0.1022	15.5706	15.70	0.408055	0.57915	0.1165	0.0000
213.7	0.203	0.3122	47.5429		0.125478		0.2529	2.4215
220.0	0.209	0.3148	47.9440	48.80	0.122649	0.23442	0.2546	2.5277
450.6	0.428	0.3804	57.9400		0.071893		0.2973	6.0535
520.0	0.494	0.3939	59.9886	60.60	0.064943	0.05516	0.3060	7.0392
687.5	0.653	0.4206	64.0625		0.053446		0.3234	9.3439
820.0	0.779	0.4379	66.6938	66.80	0.047360	0.04137	0.3346	11.1122
924.4	0.878	0.4498	68.5108		0.043660		0.3424	12.4815
1161.3	1.103	0.4730	72.0359		0.037464		0.3574	15.5258
1398.1	1.328	0.4922	74.9687		0.033133		0.3700	18.5084
1635.0	1.553	0.5088	77.4866		0.029909		0.3807	21.4450
1720.0	1.633	0.5142	78.3105	78.60	0.028941	0.02620	0.3842	22.4897
1871.9	1.778	0.5233	79.6962		0.027400		0.3901	24.3474
2108.8	2.002	0.5362	81.6670		0.025382		0.3985	27.2241
2345.7	2.227	0.5479	83.4471		0.023718		0.4061	30.0826
2582.5	2.452	0.5586	85.0711		0.022318		0.4131	32.9243
2819.4	2.677	0.5684	86.5648		0.021122		0.4194	35.7547
2920.0	2.773	0.5723	87.1645	87.30	0.020664	0.01931	0.4220	36.9511
3056.3	2.902	0.5775	87.9478		0.020085		0.4253	38.5733
3293.2	3.127	0.5859	89.2358		0.019177		0.4308	41.3894
3530.1	3.352	0.5938	90.4411		0.018373		0.4360	44.1991
3766.9	3.577	0.6013	91.5738		0.017656		0.4408	47.0046
3820.0	3.627	0.6029	91.8185	92.00	0.017506	0.01655	0.4419	47.6314
4003.8	3.802	0.6083	92.6423		0.017012		0.4454	49.8062
4240.7	4.027	0.6149	93.6534		0.016429		0.4497	52.6118
4477.6	4.252	0.6212	94.6119		0.015899		0.4538	55.5609
4714.5	4.477	0.6272	95.5223		0.015415		0.4577	58.3819
4951.3	4.702	0.6329	96.3915		0.014971		0.4614	61.0459
5020.0	4.767	0.6345	96.6365	96.70	0.014848	0.01379	0.4624	61.8763
5188.2	4.927	0.6384	97.2227		0.014560		0.4649	63.9867
5425.1	5.152	0.6436	98.0173		0.014181		0.4683	66.8374
5662.0	5.377	0.6486	98.7799		0.013829		0.4716	69.5536
5898.9	5.601	0.6534	99.5137		0.013500		0.4747	72.3770
5980.0	5.679	0.6550	99.7584	99.10	0.013393	0.01241	0.4757	73.3958
6135.7	5.826	0.6580	100.2188		0.013193		0.4777	75.3114
6372.6	6.051	0.6625	100.8977		0.012906		0.4806	78.1277
6609.5	6.276	0.6668	101.5533		0.012636		0.4834	80.8317
6846.4	6.501	0.6709	102.1872		0.012382		0.4861	83.7240
7000.0	6.647	0.6736	102.5866	100.30	0.012225	0.01172	0.4878	85.6516
7083.3	6.726	0.6750	102.7993		0.012143		0.4887	86.6782
7320.1	6.951	0.6789	103.3914		0.011916		0.4913	89.5315
7557.0	7.176	0.6826	103.9654		0.011702		0.4937	92.2881
7793.9	7.401	0.6863	104.5229		0.011499		0.4961	95.0663
8030.8	7.626	0.6898	105.0635		0.011306		0.4984	98.0970
8267.7	7.851	0.6933	105.5881		0.011122		0.5006	101.0394

8504.5	8.076	0.6966	106.0979		0.010947		0.5028	103.8976
8560.0	8.128	0.6974	106.2153	106.20	0.010907	0.01103	0.5033	104.5549
8741.4	8.301	0.6999	106.5941		0.010780		0.5049	106.6740
8978.3	8.526	0.7031	107.0779		0.010620		0.5070	109.4920
9215.2	8.751	0.7062	107.5488		0.010468		0.5090	112.5652
9452.1	8.976	0.7092	108.0072		0.010322		0.5110	115.5627
9688.9	9.200	0.7121	108.4540		0.010182		0.5129	118.4882
9760.0	9.268	0.7130	108.5860	108.90	0.010141	0.01034	0.5134	119.3513
9925.8	9.425	0.7150	108.8902		0.010048		0.5147	121.3418
10162.7	9.650	0.7178	109.3165		0.009919		0.5165	124.1265
10399.6	9.875	0.7205	109.7332		0.009795		0.5183	127.1212
10480.0	9.952	0.7214	109.8724	110.90	0.009754	0.01034	0.5189	128.1827
10636.5	10.100	0.7232	110.1399		0.009675		0.5201	130.2247
10873.3	10.325	0.7258	110.5372		0.009561		0.5218	133.2639
11110.2	10.550	0.7283	110.9257		0.009450		0.5234	136.2403
11347.1	10.775	0.7308	111.3059		0.009343		0.5250	139.1559
11584.0	11.000	0.7333	111.6783		0.009240		0.5266	142.0124

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_{rw}	k_{ro}
0.050	0.0000E+00	0.1000E+01
0.082	0.5083E-04	0.9318E+00
0.115	0.4151E-03	0.8650E+00
0.147	0.1418E-02	0.7996E+00
0.180	0.3390E-02	0.7355E+00
0.212	0.6664E-02	0.6730E+00
0.245	0.1158E-01	0.6120E+00
0.277	0.1847E-01	0.5527E+00
0.310	0.2768E-01	0.4950E+00
0.342	0.3955E-01	0.4392E+00
0.375	0.5442E-01	0.3852E+00
0.407	0.7264E-01	0.3332E+00
0.440	0.9455E-01	0.2833E+00
0.472	0.1205E+00	0.2357E+00
0.505	0.1508E+00	0.1907E+00
0.538	0.1859E+00	0.1484E+00
0.570	0.2261E+00	0.1091E+00
0.603	0.2716E+00	0.7344E-01
0.635	0.3230E+00	0.4203E-01
0.668	0.3805E+00	0.1619E-01
0.700	0.4444E+00	0.0000E+00

RUN NO. 4 - SUMMARY OF COMPUTER HISTORY MATCH RESULTS

A: Displacement Parameters.

Core Length, cm	44.3
Cross-sectional Area sq. cm	25.6
Core diameter, cm	5.7
Porosity	0.358
Pore Volume, ml	406
Absolute Permeability, Darcy	3.49
Viscosity of Displacing Fluid, mPa.s	1
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.72
End Point Rel. Perm. of Displacing Fluid	0.43
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.05
Injection Rate, ml/sec	0.0892
Flood Velocity, m/day	8.4
Initial Pressure Drop, MPa	2.315
a_w	2.88
K_o	1.52

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		2.315367		0.0500	0.0000
80.0	0.018	0.0270	7.1339	7.30	2.132981	2.41315	0.0676	0.0000
200.0	0.044	0.0676	17.8349	12.30	1.859402	2.75788	0.0939	0.0000
320.0	0.070	0.1081	28.5358	17.00	1.585823	2.82683	0.1203	0.0000
440.0	0.097	0.1487	39.2367	25.60	1.312243	2.48209	0.1466	0.0000
777.2	0.171	0.2626	69.3105		0.543378		0.2207	2.2175
1040.0	0.228	0.2863	75.5670	60.70	0.434096	0.55158	0.2361	3.3132
1640.0	0.360	0.3240	85.5028	81.30	0.311104	0.38610	0.2606	5.5873
1804.1	0.396	0.3321	87.6319		0.290704		0.2658	6.1779
2540.0	0.558	0.3617	95.4503	98.20	0.228908	0.24821	0.2851	8.7270
2831.0	0.622	0.3713	97.9948		0.212468		0.2914	9.7010
3080.0	0.677	0.3789	99.9958	109.60	0.200587	0.20684	0.2963	10.5225
3680.0	0.809	0.3952	104.2899	110.00	0.177824	0.17237	0.3069	12.4656
3857.9	0.848	0.3996	105.4449		0.172273		0.3097	13.0327
4640.0	1.019	0.4169	110.0287	113.10	0.152315	0.15168	0.3210	15.4905
4884.8	1.073	0.4218	111.3243		0.147218		0.3242	16.2486
5840.0	1.283	0.4392	115.8919	118.10	0.130907	0.13238	0.3354	19.1674
5911.6	1.299	0.4403	116.2074		0.129868		0.3362	19.3827
6938.5	1.524	0.4562	120.3969		0.117027		0.3465	22.4603
7040.0	1.547	0.4577	120.7809	121.00	0.115933	0.11859	0.3475	22.7607
7965.4	1.750	0.4702	124.0736		0.107074		0.3556	25.4910
8240.0	1.810	0.4736	124.9858	124.50	0.104774	0.10204	0.3578	26.2951
8992.3	1.976	0.4826	127.3541		0.099[illegible]		0.3637	28.4867
10019.1	2.201	0.4938	130.3188		0.092530		0.3710	31.4526
10160.0	2.232	0.4953	130.7043	130.90	0.091718	0.08549	0.3719	31.8582
11046.0	2.427	0.5041	133.0254		0.087017		0.3776	34.3973
12072.9	2.652	0.5135	135.5167		0.082311		0.3838	37.3218
12500.0	2.746	0.5172	136.4975	138.00	0.080548	0.07308	0.3862	38.5314
13099.8	2.878	0.5223	137.8255		0.078237		0.3895	40.2291
14126.6	3.104	0.5304	139.9775		0.074670		0.3948	43.1264
15153.5	3.329	0.5381	141.9932		0.071516		0.3997	46.0104
15620.0	3.432	0.5414	142.8685	142.20	0.070200	0.06343	0.4019	47.3351
16180.4	3.555	0.5452	143.8875		0.068705		0.4044	49.0403
17207.3	3.781	0.5520	145.6699		0.066184		0.4088	51.9965
18234.2	4.006	0.5584	147.3585		0.063905		0.4130	54.7507
19261.0	4.232	0.5645	148.9665		0.061829		0.4169	57.5948
20287.9	4.457	0.5703	150.4945		0.059934		0.4207	60.5919
20720.0	4.552	0.5726	151.1157	150.10	0.059184	0.05171	0.4222	61.8017
21314.8	4.683	0.5758	151.9517		0.058195		0.4243	63.4197
22100.0	4.855	0.5799	153.0243	152.20	0.056956	0.04895	0.4269	65.4750
22341.7	4.909	0.5811	153.3478		0.056590		0.4277	66.0898
23368.5	5.134	0.5862	154.6878		0.055103		0.4310	69.0554
24395.4	5.360	0.5910	155.9711		0.053724		0.4342	72.0206
25422.3	5.585	0.5957	157.2044		0.052440		0.4372	74.8481
26060.0	5.725	0.5985	157.9477	157.10	0.051685	0.04413	0.4390	76.5384

26449.2	5.811	0.6002	158.3935		0.051240		0.4401	77.5458
26640.0	5.897	0.6019	158.8355	157.90	0.050803	0.04275	0.4412	78.5400
27476.0	6.037	0.6046	159.5426		0.050114		0.4430	80.3658
28502.9	6.262	0.6088	160.6502		0.049057		0.4457	83.3924
29529.8	6.488	0.6128	161.7195		0.048064		0.4483	86.3031
30556.7	6.713	0.6167	162.7542		0.047127		0.4509	89.1027
31583.6	6.939	0.6205	163.7579		0.046240		0.4533	91.7964
32610.4	7.165	0.6242	164.7329		0.045400		0.4557	94.6048
33637.3	7.390	0.6278	165.6779		0.044604		0.4581	97.6564
34664.2	7.616	0.6313	166.5945		0.043848		0.4603	100.6117
35691.1	7.841	0.6347	167.4852		0.043129		0.4625	103.4743
36717.9	8.067	0.6379	168.3521		0.042443		0.4647	106.2465
37744.8	8.293	0.6411	169.1973		0.041789		0.4667	108.9331
38771.7	8.518	0.6443	170.0217		0.041163		0.4688	111.8221
39798.6	8.744	0.6473	170.8243		0.040565		0.4707	114.8904
40825.5	8.970	0.6503	171.6061		0.039993		0.4727	117.8786
41852.3	9.195	0.6532	172.3687		0.039444		0.4746	120.7894
42879.2	9.421	0.6560	173.1136		0.038918		0.4764	123.6246
43906.1	9.646	0.6587	173.8418		0.038412		0.4782	126.3867
44933.0	9.872	0.6614	174.5546		0.037925		0.4799	129.0781
45959.9	10.098	0.6641	175.2523		0.037457		0.4817	132.0891
46400.0	10.194	0.6652	175.5463	175.60	0.037261	0.03172	0.4824	133.4231
46986.7	10.323	0.6667	175.9339		0.037005		0.4833	135.1820
48013.6	10.549	0.6692	176.6003		0.036571		0.4850	138.2081
49040.5	10.774	0.6717	177.2525		0.036151		0.4866	141.1702
50067.4	11.000	0.6741	177.8914		0.035747		0.4882	144.0689

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_{rl}	k_{rp}
0.050	0.0000E+00	0.1000E+01
0.082	0.1074E-03	0.9250E+00
0.115	0.7910E-03	0.8520E+00
0.147	0.2543E-02	0.7811E+00
0.180	0.5823E-02	0.7124E+00
0.212	0.1107E-01	0.6458E+00
0.245	0.1872E-01	0.5815E+00
0.277	0.2918E-01	0.5196E+00
0.310	0.4286E-01	0.4600E+00
0.342	0.6017E-01	0.4030E+00
0.375	0.8151E-01	0.3487E+00
0.407	0.1072E+00	0.2971E+00
0.440	0.1378E+00	0.2484E+00
0.472	0.1735E+00	0.2028E+00
0.505	0.2148E+00	0.1604E+00
0.538	0.2620E+00	0.1216E+00
0.570	0.3155E+00	0.8661E-01
0.603	0.3757E+00	0.5593E-01
0.635	0.4430E+00	0.3020E-01
0.668	0.5176E+00	0.1053E-01
0.700	0.6000E+00	0.0000E+00

RUN NO. 5 - SUMMARY OF COMPUTER HISTORY MATCH RESULTS

A: Displacement Parameters.

Core Length, cm	20.3
Cross-sectional Area sq. cm	66.6
Core diameter, cm	9.2
Porosity	0.344
Pore Volume, ml	465.08
Absolute Permeability, Darcy	3.27
Viscosity of Displacing Fluid, mPa.s	1.0
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.80
End Point Rel. Perm. of Displacing Fluid	0.30
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.069
Injection Rate, ml/sec	0.2225
Flood Velocity, m/day	8.4
Initial Pressure Drop, MPa	0.9782
c_w	2.8
c_o	1.2

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		0.978160		0.0690	0.0000
120.0	0.057	0.0905	26.5663	9.00	0.733660	0.66189	0.1261	0.0065
240.0	0.115	0.1811	53.1326	26.20	0.489160	0.52400	0.1832	0.0065
354.7	0.170	0.2676	78.5200		0.255510		0.2378	1.6816
600.0	0.287	0.3197	93.8278	77.80	0.169234	0.22063	0.2707	3.6006
826.3	0.395	0.3519	103.2745		0.133779		0.2911	5.1869
900.0	0.431	0.3607	105.8407	101.70	0.125803	0.15168	0.2966	5.6841
1200.0	0.574	0.3907	114.6526	119.80	0.102612	0.11032	0.3155	7.6420
1297.9	0.621	0.3990	117.1057		0.097141		0.3208	8.2634
1500.0	0.718	0.4147	121.6909	126.90	0.087875	0.09377	0.3307	9.5237
1769.6	0.847	0.4329	127.0279		0.078460		0.3421	11.1699
2241.2	1.072	0.4595	134.8506		0.066864		0.3590	13.9768
2400.0	1.148	0.4674	137.1607	142.80	0.063864	0.06343	0.3639	14.9056
2712.8	1.298	0.4816	141.3435		0.058857		0.3729	16.7168
3184.4	1.523	0.5006	146.9110		0.052944		0.3849	19.4084
3656.1	1.749	0.5172	151.7940		0.048368		0.3954	22.0647
3720.0	1.780	0.5194	152.4125	156.30	0.047825	0.04619	0.3967	22.4236
4127.7	1.975	0.5321	156.1484		0.044706		0.4047	24.6940
4599.3	2.200	0.5455	160.0811		0.041697		0.4132	27.3054
4800.0	2.296	0.5508	161.6461	165.10	0.040571	0.03930	0.4166	28.4111
5070.9	2.426	0.5577	163.6689		0.039173		0.4209	29.8987
5542.6	2.652	0.5690	166.9691		0.037021		0.4280	32.4816
6000.0	2.870	0.5791	169.9364	173.40	0.035213	0.03378	0.4344	34.9785
6014.2	2.877	0.5794	170.0252		0.035161		0.4346	35.0562
6485.8	3.103	0.5891	172.8716		0.033533		0.4407	37.6224
6957.5	3.329	0.5981	175.5358		0.032095		0.4464	40.1848
7429.1	3.554	0.6067	178.0372		0.030815		0.4518	42.8528
7800.0	3.732	0.6130	179.9008	182.20	0.029902	0.02896	0.4558	44.8771
7900.7	3.780	0.6147	180.3927		0.029667		0.4569	45.4074
8372.3	4.005	0.6223	182.6254		0.028629		0.4617	47.9241
8844.0	4.231	0.6295	184.7418		0.027686		0.4662	50.5659
9315.6	4.457	0.6364	186.7555		0.026825		0.4706	53.0524
9600.0	4.593	0.6404	187.9263	188.70	0.026341	0.02551	0.4731	54.5784
9787.2	4.682	0.6429	188.6786		0.026035		0.4747	55.6568
10258.8	4.908	0.6492	190.5136		0.025308		0.4786	58.2772
10730.5	5.134	0.6552	192.2713		0.024635		0.4824	60.7659
11202.1	5.359	0.6609	193.9595		0.024010		0.4860	63.3745
11400.0	5.454	0.6633	194.6470	194.60	0.023761	0.02275	0.4875	64.5033
11673.7	5.585	0.6664	195.5789		0.023429		0.4895	66.0306
12145.3	5.810	0.6718	197.1368		0.022886		0.4929	68.5726
12617.0	6.036	0.6769	198.6399		0.022378		0.4961	71.0770
13088.6	6.262	0.6818	200.0890		0.021901		0.4992	73.8118
13560.2	6.487	0.6866	201.4870		0.021452		0.5022	76.4461
14031.9	6.713	0.6912	202.8392		0.021030		0.5051	78.9841

14160.0	6.774	0.6924	203.1992	202.30	0.020919	0.01999	0.5059	79.6574
14503.5	6.939	0.6956	204.1496		0.020630		0.5080	81.5626
14975.1	7.164	0.7000	205.4178		0.020253		0.5107	84.3195
15446.7	7.390	0.7042	206.6463		0.019895		0.5133	86.9904
15918.4	7.616	0.7082	207.8387		0.019555		0.5159	89.5775
16320.0	7.808	0.7116	208.8280	207.60	0.019279	0.01862	0.5180	91.7179
16390.0	7.841	0.7122	208.9981		0.019232		0.5184	92.0930
16861.6	8.067	0.7160	210.1247		0.018924		0.5208	94.9202
17333.2	8.292	0.7197	211.2191		0.018631		0.5232	97.6715
17804.9	8.518	0.7234	212.2838		0.018356		0.5254	100.3503
18276.5	8.744	0.7269	213.3212		0.018083		0.5277	102.9577
18720.0	8.956	0.7301	214.2734	212.30	0.017842	0.01724	0.5297	105.3984
18748.1	8.969	0.7304	214.3331		0.017827		0.5299	105.5721
19219.8	9.195	0.7337	215.3191		0.017582		0.5320	108.4397
19691.4	9.421	0.7370	216.2800		0.017346		0.5340	111.2425
20163.0	9.646	0.7402	217.2174		0.017121		0.5361	113.9825
20634.6	9.872	0.7433	218.1330		0.016904		0.5380	116.6605
21106.3	10.097	0.7463	219.0282		0.016695		0.5399	119.2789
21120.0	10.104	0.7464	219.0540	215.80	0.016689	0.01655	0.5400	119.3539
21577.9	10.323	0.7493	219.9035		0.016494		0.5418	122.1491
22049.5	10.549	0.7522	220.7584		0.016300		0.5437	125.0488
22521.1	10.774	0.7551	221.5941		0.016114		0.5455	127.8919
22992.8	11.000	0.7579	222.4116		0.015934		0.5472	130.6810

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_w	k_{ro}
0.050	0.0000E+00	0.1000E+01
0.082	0.7704E-04	0.9409E+00
0.115	0.5526E-03	0.8825E+00
0.147	0.1750E-02	0.8246E+00
0.180	0.3964E-02	0.7673E+00
0.212	0.7475E-02	0.7108E+00
0.245	0.1255E-01	0.6549E+00
0.277	0.1945E-01	0.5998E+00
0.310	0.2843E-01	0.5454E+00
0.342	0.3974E-01	0.4919E+00
0.375	0.5362E-01	0.4393E+00
0.407	0.7030E-01	0.3877E+00
0.440	0.9003E-01	0.3371E+00
0.472	0.1130E+00	0.2877E+00
0.505	0.1395E+00	0.2396E+00
0.538	0.1698E+00	0.1930E+00
0.570	0.2040E+00	0.1481E+00
0.603	0.2423E+00	0.1052E+00
0.635	0.2851E+00	0.6505E-01
0.668	0.3324E+00	0.2857E-01
0.700	0.3846E+00	0.0000E+00

RUN NO. 6 - SUMMARY OF COMPUTER HISTORY MATCH RESULTS

A: Displacement Parameters.

Core Length, cm	25.1
Cross-sectional Area sq. cm	66.6
Core diameter, cm	9.2
Porosity	0.353
Pore Volume, ml	590.1
Absolute Permeability, Darcy	2.5
Viscosity of Displacing Fluid, mPa.s	3.33
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.75
End Point Rel. Perm. of Displacing Fluid	0.3
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.091
Injection Rate, ml/sec	0.2225
Flood Velocity, m/day	8.2
Initial Pressure Drop, MPa	1.258
ϵ_w	3.1
ϵ_o	1.2

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		1.257827		0.0910	0.0000
120.0	0.045	0.0728	26.1715	11.10	1.016830	0.96526	0.1354	0.0242
240.0	0.090	0.1457	52.3431	24.70	0.775834	0.91010	0.1797	0.0242
360.0	0.136	0.2185	78.5146	45.90	0.534838	0.62052	0.2241	0.0242
455.3	0.172	0.2763	99.3022		0.343418		0.2593	1.6369
480.0	0.181	0.2820	101.3392	66.60	0.328320	0.44816	0.2627	1.8152
720.0	0.271	0.3243	116.5489	88.80	0.236570	0.24131	0.2885	3.3656
1020.0	0.385	0.3605	129.5526	118.30	0.181716	0.16547	0.3105	5.1205
1053.6	0.397	0.3639	130.7733		0.177405		0.3126	5.3104
1140.0	0.430	0.3722	133.7520	128.70	0.167402	0.15168	0.3177	5.7944
1500.0	0.566	0.4014	144.2648	152.20	0.137207	0.13100	0.3355	7.7553
1651.9	0.623	0.4119	148.0191		0.128078		0.3418	8.5613
2100.0	0.792	0.4383	157.5106	181.30	0.108139	0.10066	0.3579	10.8908
2250.2	0.848	0.4460	160.2842		0.103053		0.3626	11.6586
2700.0	1.018	0.4666	167.6951	185.40	0.090849	0.07998	0.3752	13.9253
2848.5	1.074	0.4728	169.8983		0.087572		0.3789	14.6651
3446.8	1.300	0.4949	177.8435		0.076910		0.3924	17.6126
3900.0	1.471	0.5094	183.0739	193.70	0.070765	0.06205	0.4012	19.8178
4045.1	1.525	0.5138	184.6326		0.069053		0.4039	20.5180
4643.4	1.751	0.5303	190.5698		0.062984		0.4139	23.3964
4800.0	1.810	0.5343	192.0097	196.80	0.061614	0.05378	0.4164	24.1446
5241.6	1.976	0.5450	195.8512		0.058134		0.4229	26.2518
5700.0	2.149	0.5552	199.5389	201.70	0.055021	0.04688	0.4291	28.4265
5839.9	2.202	0.5582	200.6109		0.054155		0.4310	29.0894
6438.2	2.428	0.5703	204.9450		0.050821		0.4383	31.9179
7036.5	2.653	0.5814	208.9248		0.047981		0.4451	34.7388
7260.0	2.737	0.5853	210.3320	212.30	0.047024	0.04068	0.4474	35.7909
7634.8	2.879	0.5916	212.6048		0.045528		0.4513	37.5548
8233.1	3.104	0.6011	216.0275		0.043384		0.4571	40.3671
8280.0	3.122	0.6019	216.2860	217.20	0.043227	0.03723	0.4575	40.5861
8831.4	3.330	0.6100	219.2268		0.041492		0.4625	43.1779
9360.0	3.529	0.6174	221.8886	223.40	0.039995	0.03723	0.4670	45.7406
9429.7	3.556	0.6184	222.2285		0.039808		0.4676	46.0834
10028.0	3.781	0.6262	225.0515		0.038299		0.4724	48.9161
10560.0	3.982	0.6329	227.4348	227.10	0.037080	0.03447	0.4764	51.3276
10626.3	4.007	0.6337	227.7239		0.036936		0.4769	51.6617
11224.6	4.232	0.6407	230.2555		0.035699		0.4812	54.5820
11822.8	4.458	0.6474	232.6618		0.034569		0.4853	57.3371
12421.1	4.683	0.6538	234.9579		0.033533		0.4892	60.1952
13019.4	4.909	0.6599	237.1474		0.032580		0.4929	63.0895
13560.0	5.113	0.6652	239.0445	238.30	0.031781	0.03034	0.4961	65.5839
13617.7	5.135	0.6657	239.2429		0.031698		0.4964	65.8436
14216.0	5.360	0.6713	241.2541		0.030880		0.4998	68.7302
14814.3	5.586	0.6767	243.1821		0.030120		0.5031	71.6614
15060.0	5.678	0.6788	243.9519	242.60	0.029822	0.02896	0.5044	72.8294

15412.6	5.811	0.6819	245.0359		0.029410		0.5062	74.4704
16010.9	6.037	0.6868	246.8234		0.028745		0.5093	77.2731
16260.0	6.131	0.6888	247.5483	246.30	0.028481	0.02758	0.5105	78.5415
16609.2	6.263	0.6916	248.5453		0.028122		0.5122	80.2877
17207.5	6.488	0.6962	250.2060		0.027536		0.5150	83.1947
17805.8	6.714	0.7007	251.8116		0.026984		0.5177	85.9989
18180.0	6.855	0.7034	252.7903	250.60	0.026654	0.02620	0.5194	87.7472
18404.0	6.939	0.7050	253.3667		0.026462		0.5204	88.9101
19002.3	7.165	0.7092	254.8706		0.025969		0.5229	91.9496
19600.6	7.391	0.7133	256.3271		0.025502		0.5254	94.8967
20198.9	7.616	0.7172	257.7404		0.025059		0.5278	97.7546
20340.0	7.669	0.7181	258.0678	255.60	0.024957	0.02482	0.5283	98.4152
20797.2	7.842	0.7210	259.1141		0.024637		0.5301	100.6284
21395.5	8.067	0.7247	260.4476		0.024236		0.5324	103.7457
21993.8	8.293	0.7283	261.7429		0.023853		0.5346	106.7812
22592.1	8.519	0.7318	263.0027		0.023488		0.5367	109.7385
23190.4	8.744	0.7353	264.2300		0.023140		0.5388	112.6198
23700.0	8.936	0.7381	265.2513	261.80	0.022854	0.02275	0.5405	115.1584
23788.7	8.970	0.7386	265.4267		0.022806		0.5408	115.6332
24387.0	9.195	0.7418	266.5917		0.022486		0.5428	118.7970
24985.2	9.421	0.7450	267.7270		0.022180		0.5447	121.8911
25583.5	9.646	0.7481	268.8344		0.021886		0.5466	124.9173
26181.8	9.872	0.7511	269.9159		0.021603		0.5484	127.8771
26780.1	10.098	0.7540	270.9733		0.021332		0.5502	130.8362
27180.0	10.248	0.7560	271.6663	268.60	0.021156	0.02137	0.5514	133.0237
27378.4	10.323	0.7569	272.0060		0.021070		0.5520	134.0986
27976.7	10.549	0.7597	273.0144		0.020819		0.5537	137.3004
28575.0	10.774	0.7624	274.0002		0.020576		0.5553	140.4414
29173.3	11.000	0.7651	274.9645		0.020342		0.5570	143.5253

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_{rl}	k_{rp}
0.050	0.0000E+00	0.1000E+01
0.082	0.2847E-04	0.9404E+00
0.115	0.2594E-03	0.8815E+00
0.147	0.9449E-03	0.8232E+00
0.180	0.2364E-02	0.7655E+00
0.212	0.4816E-02	0.7086E+00
0.245	0.8612E-02	0.6524E+00
0.277	0.1408E-01	0.5970E+00
0.310	0.2155E-01	0.5424E+00
0.342	0.3137E-01	0.4888E+00
0.375	0.4389E-01	0.4361E+00
0.407	0.5947E-01	0.3844E+00
0.440	0.7849E-01	0.3338E+00
0.472	0.1013E+00	0.2845E+00
0.505	0.1283E+00	0.2365E+00
0.538	0.1599E+00	0.1901E+00
0.570	0.1964E+00	0.1456E+00
0.603	0.2383E+00	0.1031E+00
0.635	0.2859E+00	0.6347E-01
0.668	0.3397E+00	0.2768E-01
0.700	0.4000E+00	0.0000E+00

RUN NO. 7 - SUMMARY OF COMPUTER HISTORY MATCH RESULTS

A: Displacement Parameters.

Core Length, cm	38.4
Cross-sectional Area sq. cm	11.4
Core diameter, cm	3.8
Porosity	0.352
Pore Volume, ml	154.09
Absolute Permeability, Darcy	2.98
Viscosity of Displacing Fluid, mPa.s	1
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.7
End Point Rel. Perm. of Displacing Fluid	0.42
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.05
Injection Rate, ml/sec	0.0442
Flood Velocity, m/day	9.5
Initial Pressure Drop, MPa	2.659
c_w	1.8
c_o	1.1

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		2.658647		0.0500	0.0000
60.0	0.017	0.0265	2.6544	2.00	2.158134	1.06178	0.0672	0.0000
217.2	0.062	0.0959	9.6082		0.846903		0.1124	0.8472
240.0	0.069	0.1011	10.1277	10.00	0.784323	1.21347	0.1157	1.0380
360.0	0.103	0.1227	12.2934	11.50	0.585167	0.96526	0.1298	1.8831
960.0	0.275	0.1836	18.3910	13.00	0.303393	0.27579	0.1694	5.0414
1011.6	0.290	0.1873	18.7621		0.293258		0.1718	5.2763
1806.0	0.518	0.2321	23.2502		0.202249		0.2009	8.5511
1920.0	0.551	0.2373	23.7679	17.00	0.194552	0.16547	0.2042	8.9834
2600.4	0.746	0.2643	26.4681		0.160693		0.2218	11.4345
3120.0	0.895	0.2816	28.2027	32.10	0.143377	0.11721	0.2330	13.1929
3394.8	0.974	0.2899	29.0365		0.136025		0.2384	14.0924
4189.2	1.202	0.3115	31.1996		0.119370		0.2525	16.5986
4983.6	1.430	0.3302	33.0691		0.107265		0.2646	18.2418
5778.0	1.657	0.3467	34.7222		0.098002		0.2753	21.4138
5820.0	1.669	0.3475	34.8052	35.80	0.097569	0.07722	0.2759	21.5155
6572.4	1.885	0.3616	36.2223		0.090596		0.2851	23.7738
7366.8	2.113	0.3752	37.5846		0.084550		0.2939	25.9650
7740.0	2.220	0.3813	38.1883	39.50	0.082063	0.06757	0.2978	26.8739
8161.2	2.341	0.3879	38.8472		0.079474		0.3021	27.9233
8955.6	2.569	0.3995	40.0182		0.075151		0.3097	30.2430
9000.0	2.582	0.4002	40.0811	41.40	0.074928	0.06067	0.3101	30.3637
9750.0	2.797	0.4104	41.1097		0.071421		0.3168	32.2795
10544.4	3.025	0.4207	42.1395		0.068151		0.3235	34.0793
10980.0	3.150	0.4261	42.6802	46.00	0.066522	0.05516	0.3270	35.3364
11338.8	3.252	0.4304	43.1120		0.065260		0.3298	36.3285
12133.2	3.480	0.4396	44.0296		0.062688		0.3357	38.3729
12927.7	3.708	0.4483	44.9026		0.060378		0.3414	40.2302
13140.0	3.769	0.4506	45.1294	47.90	0.059799	0.04826	0.3429	40.6980
13722.1	3.936	0.4567	45.7383		0.058284		0.3468	42.0502
14516.5	4.164	0.4646	46.5355		0.056381		0.3520	44.1848
15310.9	4.392	0.4722	47.2972		0.054644		0.3569	46.1621
16105.3	4.620	0.4795	48.0284		0.053048		0.3617	47.9979
16500.0	4.733	0.4830	48.3818	50.60	0.052302	0.04344	0.3640	48.8617
16899.7	4.848	0.4866	48.7335		0.051575		0.3663	49.7059
17694.1	5.075	0.4934	49.4140		0.050208		0.3707	51.6971
18480.0	5.301	0.4998	50.0616	52.50	0.048954	0.03999	0.3749	53.6870
18488.5	5.303	0.4999	50.0685		0.048941		0.3749	53.7079
19282.9	5.531	0.5062	50.6998		0.047761		0.3790	55.6031
20077.3	5.759	0.5123	51.3109		0.046658		0.3830	57.3919
20871.7	5.987	0.5182	51.9038		0.045624		0.3868	59.0824
21666.1	6.215	0.5240	52.4802		0.044650		0.3906	60.9289
22460.5	6.443	0.5295	53.0383		0.043734		0.3942	62.9327
22560.0	6.471	0.5302	53.1069	52.50	0.043623	0.03585	0.3946	63.1770
23254.9	6.670	0.5349	53.5795		0.042871		0.3977	64.8441

24049.3	6.898	0.5402	54.1054		0.042054		0.4011	66.6692
24843.7	7.126	0.5453	54.6175		0.041281		0.4044	68.4134
25020.0	7.177	0.5464	54.7295	54.70	0.041115	0.03378	0.4052	68.7899
25638.1	7.354	0.5503	55.1172		0.040547		0.4077	70.0815
26432.5	7.582	0.5552	55.6053		0.039848		0.4109	71.8668
27226.9	7.810	0.5599	56.0804		0.039183		0.4139	73.8522
27840.0	7.986	0.5635	56.4387	57.00	0.038692	0.03172	0.4163	75.3343
28021.3	8.038	0.5645	56.5433		0.038550		0.4169	75.7646
28815.7	8.266	0.5690	56.9950		0.037946		0.4199	77.6076
29610.1	8.493	0.5734	57.4363		0.037369		0.4227	79.3841
30404.5	8.721	0.5778	57.8681		0.036817		0.4255	81.0984
30720.0	8.812	0.5794	58.0370	58.10	0.036604	0.02965	0.4266	81.7622
31198.9	8.949	0.5820	58.2910		0.036287		0.4283	82.7525
31993.4	9.177	0.5861	58.7056		0.035778		0.4310	84.5199
32787.8	9.405	0.5902	59.1110		0.035291		0.4336	86.4925
33582.2	9.633	0.5941	59.5075		0.034822		0.4362	88.4070
34376.6	9.861	0.5980	59.8956		0.034372		0.4387	90.2648
34380.0	9.862	0.5980	59.8973	59.20	0.034370	0.02827	0.4387	90.2728
35171.0	10.089	0.6018	60.2760		0.033939		0.4412	92.0687
35965.4	10.316	0.6055	60.6491		0.033521		0.4436	93.8214
36759.8	10.544	0.6092	61.0154		0.033118		0.4460	95.5240
37554.2	10.772	0.6128	61.3754		0.032729		0.4483	97.1784
38348.6	11.000	0.6163	61.7294		0.032353		0.4506	98.9370

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_{ri}	k_{rp}
0.050	0.0000E+00	0.1000E+01
0.082	0.2709E-02	0.9466E+00
0.115	0.9434E-02	0.8934E+00
0.147	0.1957E-01	0.8404E+00
0.180	0.3285E-01	0.7876E+00
0.212	0.4909E-01	0.7350E+00
0.245	0.6816E-01	0.6827E+00
0.277	0.8995E-01	0.6307E+00
0.310	0.1144E+00	0.5789E+00
0.342	0.1414E+00	0.5275E+00
0.375	0.1709E+00	0.4763E+00
0.407	0.2029E+00	0.4255E+00
0.440	0.2373E+00	0.3751E+00
0.472	0.2741E+00	0.3252E+00
0.505	0.3132E+00	0.2758E+00
0.538	0.3547E+00	0.2269E+00
0.570	0.3983E+00	0.1787E+00
0.603	0.4443E+00	0.1313E+00
0.635	0.4924E+00	0.8511E-01
0.668	0.5427E+00	0.4054E-01
0.700	0.5952E+00	0.0000E+00

RUN NO. 8 - SUMMARY OF COMPUTER HISTORY MATCH RESULTS

A: Displacement Parameters.

Core Length, cm	25.4
Cross-sectional Area sq. cm	1.3
Core diameter, cm	1.3
Porosity	0.392
Pore Volume, ml	12.62
Absolute Permeability, Darcy	3.41
Viscosity of Displacing Fluid, mPa.s	1
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.82
End Point Rel. Perm. of Displacing Fluid	0.35
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.016
Injection Rate, ml/sec	0.00483
Flood Velocity, m/day	8.4
Initial Pressure Drop, MPa	1.297
c_w	1.7
c_o	1.1

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		1.296813		0.0160	0.0000
320.8	0.123	0.1792	1.5461		0.275831		0.1386	2.0529
480.0	0.184	0.2039	1.7597	0.00	0.211187	0.09653	0.1555	3.1313
900.0	0.345	0.2482	2.1416	0.00	0.141213	0.19305	0.1858	5.5164
912.7	0.349	0.2493	2.1509		0.139971		0.1865	5.5819
1504.6	0.576	0.2906	2.5073		0.102456		0.2148	8.4172
1620.0	0.620	0.2972	2.5644	0.40	0.097883	0.42747	0.2193	8.9299
2096.4	0.803	0.3214	2.7729		0.083550		0.2358	10.9511
2688.3	1.029	0.3463	2.9886		0.071810		0.2529	13.3052
3280.2	1.256	0.3676	3.1720		0.063673		0.2674	15.5349
3420.0	1.309	0.3722	3.2117	3.50	0.062094	0.07584	0.2706	16.0475
3872.0	1.482	0.3862	3.3324		0.057636		0.2802	17.6735
4463.9	1.709	0.4028	3.4756		0.052941		0.2915	19.7410
4920.0	1.884	0.4145	3.5766	4.00	0.049965	0.05654	0.2995	21.2946
5055.8	1.936	0.4178	3.6053		0.049165		0.3018	21.7522
5647.6	2.162	0.4316	3.7241		0.046047		0.3112	23.7169
6120.0	2.343	0.4418	3.8123	4.00	0.043918	0.05102	0.3182	25.2570
6239.5	2.389	0.4443	3.8338		0.043421		0.3199	25.6433
6831.4	2.616	0.4561	3.9357		0.041174		0.3280	27.6826
7423.2	2.842	0.4671	4.0306		0.039228		0.3355	29.5676
7920.0	3.032	0.4759	4.1061	4.40	0.037779	0.04206	0.3415	30.9851
8015.1	3.069	0.4775	4.1201		0.037518		0.3426	31.2480
8607.0	3.295	0.4873	4.2046		0.036001		0.3493	33.2377
9198.8	3.522	0.4965	4.2845		0.034647		0.3556	35.0414
9790.7	3.749	0.5054	4.3606		0.033427		0.3617	36.6827
10382.6	3.975	0.5138	4.4333		0.032320		0.3674	38.5850
10974.4	4.202	0.5218	4.5025		0.031314		0.3729	40.3928
11566.3	4.428	0.5295	4.5688		0.030392		0.3782	42.0672
11760.0	4.503	0.5319	4.5900	4.40	0.030106	0.02758	0.3798	42.5885
12158.2	4.655	0.5369	4.6326		0.029542		0.3832	43.7414
12750.0	4.882	0.5440	4.6939		0.028758		0.3881	45.6040
13080.0	5.008	0.5478	4.7271	5.30	0.028346	0.02413	0.3907	46.5921
13341.9	5.108	0.5508	4.7529		0.028032		0.3928	47.3523
13933.8	5.335	0.5574	4.8097		0.027356		0.3973	48.9956
14525.6	5.561	0.5638	4.8648		0.026725		0.4016	50.6082
15117.5	5.788	0.5699	4.9180		0.026134		0.4058	52.4580
15120.0	5.789	0.5700	4.9182	5.30	0.026132	0.02137	0.4059	52.4657
15709.4	6.015	0.5759	4.9694		0.025581		0.4099	54.2144
16301.2	6.241	0.5817	5.0192		0.025061		0.4139	55.8837
16893.1	6.468	0.5873	5.0676		0.024570		0.4177	57.4719
17485.0	6.694	0.5927	5.1146		0.024107		0.4214	59.1675
17940.0	6.869	0.5968	5.1498	5.30	0.023768	0.01931	0.4242	60.5639
18076.8	6.921	0.5980	5.1603		0.023668		0.4251	60.9751
18668.7	7.148	0.6032	5.2046		0.023253		0.4286	62.7079
19260.6	7.374	0.6082	5.2478		0.022859		0.4320	64.3698

19800.0	7.581	0.6126	5.2862	5.30	0.022517	0.01724	0.4350	65.8266
19852.4	7.601	0.6131	5.2899		0.022484		0.4353	65.9653
20444.3	7.827	0.6178	5.3310		0.022127		0.4386	67.5750
21036.2	8.054	0.6225	5.3711		0.021786		0.4418	69.3976
21540.0	8.247	0.6263	5.4044	5.40	0.021508	0.01655	0.4444	70.8997
21628.0	8.281	0.6270	5.4102		0.021461		0.4449	71.1576
22219.9	8.507	0.6314	5.4483		0.021150		0.4479	72.8577
22811.8	8.734	0.6357	5.4855		0.020853		0.4508	74.5009
23220.0	8.890	0.6386	5.5107	5.40	0.020655	0.01655	0.4528	75.6027
23403.6	8.961	0.6399	5.5220		0.020568		0.4537	76.0898
23995.5	9.187	0.6441	5.5577		0.020294		0.4565	77.7275
24587.4	9.414	0.6481	5.5925		0.020031		0.4593	79.5493
24900.0	9.533	0.6502	5.6107	5.50	0.019897	0.01586	0.4608	80.4911
25179.2	9.640	0.6521	5.6267		0.019779		0.4620	81.3199
25771.1	9.867	0.6559	5.6601		0.019536		0.4647	83.0403
26363.0	10.094	0.6597	5.6928		0.019302		0.4673	84.7131
26954.8	10.320	0.6635	5.7248		0.019077		0.4698	86.3395
27546.7	10.547	0.6671	5.7563		0.018860		0.4723	87.9217
28138.6	10.773	0.6707	5.7872		0.018650		0.4747	89.6808
28730.4	11.000	0.6742	5.8175		0.018447		0.4771	91.5007

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_n	k_{rp}
0.050	0.0000E+00	0.1000E+01
0.082	0.2537E-02	0.9469E+00
0.115	0.8312E-02	0.8940E+00
0.147	0.1664E-01	0.8413E+00
0.180	0.2724E-01	0.7888E+00
0.212	0.3991E-01	0.7365E+00
0.245	0.5454E-01	0.6844E+00
0.277	0.7101E-01	0.6325E+00
0.310	0.8925E-01	0.5809E+00
0.342	0.1092E+00	0.5296E+00
0.375	0.1308E+00	0.4785E+00
0.407	0.1540E+00	0.4278E+00
0.440	0.1787E+00	0.3775E+00
0.472	0.2050E+00	0.3275E+00
0.505	0.2327E+00	0.2780E+00
0.538	0.2619E+00	0.2290E+00
0.570	0.2925E+00	0.1806E+00
0.603	0.3245E+00	0.1330E+00
0.635	0.3578E+00	0.8644E-01
0.668	0.3925E+00	0.4136E-01
0.700	0.4286E+00	0.0000E+00

RUN NO. 9 - SUMMARY OF COMPUTER HISTORY MATCH RESULTS

A: Displacement Parameters.

Core Length, cm	63.5
Cross-sectional Area sq. cm	1.3
Core diameter, cm	1.3
Porosity	0.385
Pore Volume, ml	30.97
Absolute Permeability, Darcy	4.3
Viscosity of Displacing Fluid, mPa.s	1
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.81
End Point Rel. Perm. of Displacing Fluid	0.57
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.05
Injection Rate, ml/sec	0.004833
Flood Velocity, m/day	8.5
Initial Pressure Drop, MPa	2.595
c_w	3.483
c_o	1.2899

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		2.595238		0.0500	0.0000
300.0	0.047	0.0720	1.4493	0.50	2.144887	1.25484	0.0968	0.0000
600.0	0.094	0.1440	2.8986	1.50	1.694537	1.33757	0.1436	0.0000
1200.0	0.187	0.2879	5.7972	4.90	0.793837	1.03420	0.2372	0.0000
1377.2	0.215	0.3304	6.6530		0.527892		0.2648	2.9058
2100.0	0.328	0.3661	7.3704	8.80	0.379146	0.39989	0.2879	4.9453
2817.2	0.440	0.3912	7.8762		0.304000		0.3043	6.8349
3000.0	0.468	0.3966	7.9857	8.80	0.290185	0.27579	0.3078	7.3039
4200.0	0.655	0.4262	8.5819	9.80	0.227091	0.23442	0.3271	10.2882
4257.3	0.664	0.4275	8.6063		0.224889		0.3278	10.4269
5697.3	0.889	0.4539	9.1386		0.182720		0.3450	13.8577
5700.0	0.889	0.4539	9.1395	9.80	0.182659	0.19305	0.3451	13.8640
7137.4	1.114	0.4749	9.5613		0.156002		0.3587	17.1888
7500.0	1.170	0.4796	9.6556	10.30	0.150714	0.15168	0.3617	18.0153
8577.4	1.338	0.4924	9.9134		0.137341		0.3700	20.4470
9000.0	1.404	0.4970	10.0067	10.80	0.132868	0.14479	0.3731	21.3929
10017.5	1.563	0.5074	10.2160		0.123462		0.3798	23.6517
11100.0	1.732	0.5175	10.4187	10.80	0.115124	0.11721	0.3864	26.0338
11457.5	1.788	0.5206	10.4818		0.112673		0.3884	26.8175
12897.6	2.012	0.5324	10.7190		0.104009		0.3961	29.9486
12900.0	2.013	0.5324	10.7194	10.80	0.103996	0.10618	0.3961	29.9539
14337.6	2.237	0.5430	10.9335		0.096875		0.4030	33.0546
14700.0	2.294	0.5456	10.9844	10.80	0.095271	0.09790	0.4046	33.8324
15777.7	2.462	0.5528	11.1294		0.090881		0.4093	36.1382
16500.0	2.574	0.5574	11.2216	10.80	0.088218	0.08756	0.4123	37.6782
17217.7	2.686	0.5617	11.3096		0.085763		0.4151	39.2038
18300.0	2.855	0.5680	11.4363	11.00	0.082378	0.08136	0.4192	41.4959
18657.8	2.911	0.5700	11.4767		0.081334		0.4205	42.2541
20097.8	3.136	0.5778	11.6324		0.077457		0.4255	45.2903
21300.0	3.323	0.5838	11.7547	11.30	0.074568	0.07308	0.4295	47.8219
21537.9	3.361	0.5850	11.7782		0.074030		0.4302	48.3186
22977.9	3.585	0.5918	11.9153		0.070975		0.4347	51.3388
24000.0	3.745	0.5964	12.0080	11.80	0.069000	0.06619	0.4377	53.4780
24418.0	3.810	0.5982	12.0448		0.068233		0.4389	54.3530
25858.0	4.035	0.6043	12.1674		0.065754		0.4428	57.3576
27298.1	4.259	0.6101	12.2839		0.063502		0.4466	60.3608
27300.0	4.260	0.6101	12.2841	12.00	0.063499	0.05929	0.4466	60.3649
28738.2	4.484	0.6156	12.3947		0.061445		0.4502	63.5322
30178.2	4.709	0.6209	12.5003		0.059560		0.4536	66.5860
31618.3	4.933	0.6259	12.6012		0.057822		0.4568	69.4771
33058.3	5.158	0.6307	12.6982		0.056213		0.4599	72.4303
34498.4	5.383	0.6353	12.7911		0.054721		0.4630	75.5691
35938.4	5.607	0.6397	12.8804		0.053332		0.4658	78.5664
37378.5	5.832	0.6440	12.9665		0.052034		0.4686	81.4304
38818.5	6.057	0.6481	13.0496		0.050819		0.4713	84.3946
39900.0	6.226	0.6511	13.1100	12.70	0.049956	0.04826	0.4732	86.7708

40258.6	6.282	0.6521	13.1297	0.049679	0.4739	87.5439
41698.6	6.506	0.6560	13.2071	0.048606	0.4764	90.5737
43138.7	6.731	0.6597	13.2820	0.047596	0.4788	93.4897
44578.7	6.956	0.6633	13.3547	0.046640	0.4811	96.2970
46018.8	7.180	0.6668	13.4252	0.045736	0.4834	99.4485
47458.8	7.405	0.6702	13.4935	0.044879	0.4856	102.5733
48898.9	7.630	0.6735	13.5598	0.044066	0.4878	105.5992
50338.9	7.854	0.6767	13.6243	0.043292	0.4898	108.5297
51779.0	8.079	0.6798	13.6871	0.042555	0.4919	111.3680
53219.0	8.304	0.6828	13.7483	0.041852	0.4939	114.4279
54659.1	8.528	0.6858	13.8078	0.041180	0.4958	117.6071
56099.1	8.753	0.6887	13.8658	0.040539	0.4976	120.7019
57539.2	8.978	0.6915	13.9223	0.039925	0.4995	123.7136
58979.2	9.202	0.6942	13.9775	0.039337	0.5013	126.6455
60419.3	9.427	0.6969	14.0315	0.038772	0.5030	129.5000
61859.3	9.652	0.6995	14.0843	0.038229	0.5047	132.5712
63299.4	9.877	0.7021	14.1358	0.037708	0.5064	135.7883
64739.4	10.101	0.7046	14.1862	0.037207	0.5080	138.9314
66179.5	10.326	0.7070	14.2354	0.036725	0.5096	142.0051
67619.5	10.551	0.7094	14.2836	0.036260	0.5111	145.0107
69059.6	10.775	0.7118	14.3308	0.035812	0.5127	147.9481
70499.6	11.000	0.7141	14.3771	0.035379	0.5142	150.8218

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_w	k_{ro}
0.050	0.0000E+00	0.1000E+01
0.082	0.2101E-04	0.9360E+00
0.115	0.2349E-03	0.8729E+00
0.147	0.9643E-03	0.8109E+00
0.180	0.2626E-02	0.7499E+00
0.212	0.5714E-02	0.6900E+00
0.245	0.1078E-01	0.6312E+00
0.277	0.1844E-01	0.5737E+00
0.310	0.2937E-01	0.5174E+00
0.342	0.4426E-01	0.4625E+00
0.375	0.6388E-01	0.4090E+00
0.407	0.8903E-01	0.3570E+00
0.440	0.1206E+00	0.3067E+00
0.472	0.1593E+00	0.2582E+00
0.505	0.2062E+00	0.2116E+00
0.538	0.2622E+00	0.1673E+00
0.570	0.3283E+00	0.1254E+00
0.603	0.4055E+00	0.8654E-01
0.635	0.4949E+00	0.5129E-01
0.668	0.5974E+00	0.2098E-01
0.700	0.7143E+00	0.0000E+00

RUN NO. 10 - SUMMARY OF COMPUTER HISTORY MATCH RESULTS

A: Displacement Parameters.

Core Length, cm	98.3
Cross-sectional Area sq. cm	20.3
Core diameter, cm	5.1
Porosity	0.335
Pore Volume, ml	666.84
Absolute Permeability, Darcy	3.23
Viscosity of Displacing Fluid, mPa.s	1
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.77
End Point Rel. Perm. of Displacing Fluid	0.46
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.05
Injection Rate, ml/sec	0.06666
Flood Velocity, m/day	8.5
Initial Pressure Drop, MPa	4.854
c_w	2.2
c_o	1.4

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		4.853836		0.0500	0.0000
150.0	0.015	0.0231	9.9966	10.60	4.330094	2.65446	0.0650	0.0000
450.0	0.045	0.0692	29.9898	15.90	3.282611	3.37840	0.0950	0.0000
810.0	0.081	0.1245	53.9816	39.50	2.025632	3.65419	0.1310	0.0000
1006.7	0.101	0.1548	67.0900		1.338852		0.1506	1.3091
1050.0	0.105	0.1576	68.3135	55.30	1.295230	3.34393	0.1524	1.4121
1950.0	0.195	0.1999	86.6580	81.70	0.821811	1.10315	0.1800	3.2297
3150.0	0.315	0.2354	102.0254	117.00	0.590616	0.59294	0.2030	5.2822
3278.2	0.328	0.2385	103.3655		0.574914		0.2050	5.4881
4350.0	0.435	0.2611	113.1711	132.90	0.475856	0.44126	0.2197	7.1462
5549.8	0.555	0.2816	122.0695		0.405341		0.2331	8.8967
5970.0	0.597	0.2880	124.8228	132.90	0.386475	0.34474	0.2372	9.4901
7821.3	0.782	0.3123	135.3745		0.324484		0.2530	12.0122
10092.8	1.009	0.3366	145.8808		0.275700		0.2688	14.9548
11550.0	1.155	0.3499	151.6594	161.60	0.253143	0.18616	0.2774	16.7786
12364.3	1.236	0.3568	154.6382		0.242511		0.2819	17.7804
13950.0	1.394	0.3692	160.0126	164.80	0.224843	0.10342	0.2900	19.6994
14635.9	1.463	0.3742	162.1858		0.218206		0.2932	20.5195
16650.0	1.664	0.3879	168.1242	167.80	0.201403	0.17237	0.3021	22.8930
16907.4	1.690	0.3895	168.8405		0.199499		0.3032	23.1927
19178.9	1.917	0.4033	174.8058		0.184570		0.3121	25.8136
21450.4	2.144	0.4158	180.2098		0.172339		0.3202	28.5719
23722.0	2.371	0.4271	185.1343		0.162124		0.3276	31.1571
25993.5	2.598	0.4377	189.6986		0.153406		0.3345	33.4692
28265.0	2.825	0.4474	193.9405		0.145870		0.3408	36.1856
30536.6	3.053	0.4566	197.8964		0.139289		0.3468	38.6308
32808.1	3.280	0.4652	201.6255		0.133464		0.3524	40.8535
35079.6	3.507	0.4733	205.1432		0.128273		0.3576	43.5284
37351.1	3.734	0.4809	208.4627		0.123619		0.3626	45.9917
39622.7	3.961	0.4882	211.6183		0.119411		0.3673	48.2651
39750.0	3.974	0.4886	211.7910	209.60	0.119186	0.09653	0.3676	48.3873
41894.2	4.188	0.4952	214.6340		0.115577		0.3719	50.6078
44165.7	4.415	0.5018	217.5054		0.112078		0.3762	53.1786
46437.2	4.642	0.5081	220.2473		0.108869		0.3803	55.5892
48708.8	4.869	0.5142	222.8778		0.105908		0.3842	57.8521
50980.3	5.096	0.5200	225.4118		0.103164		0.3880	60.0101
53251.8	5.323	0.5257	227.8487		0.100616		0.3917	62.6055
55523.4	5.550	0.5311	230.1904		0.098245		0.3952	65.0710
57794.9	5.777	0.5363	232.4479		0.096030		0.3986	67.4148
60066.4	6.004	0.5413	234.6311		0.093954		0.4019	69.6448
62337.9	6.232	0.5462	236.7479		0.092002		0.4050	71.7682
64609.5	6.459	0.5509	238.7983		0.090163		0.4081	74.3257
66881.0	6.686	0.5555	240.7807		0.088431		0.4111	76.8092
69152.5	6.913	0.5599	242.7020		0.086795		0.4140	79.1939
71310.0	7.128	0.5640	244.4753	238.70	0.085321	0.07584	0.4166	81.3725

71424.1	7.140	0.5642	244.5677		0.085245		0.4168	81.4855
73695.6	7.367	0.5684	246.3832		0.083774		0.4195	83.6881
74730.0	7.470	0.5703	247.1945	240.70	0.083129	0.07377	0.4207	84.6627
75967.1	7.594	0.5725	248.1529		0.082375		0.4221	85.8062
77130.0	7.710	0.5746	249.0413	244.60	0.081685	0.07170	0.4235	87.1152
78238.7	7.821	0.5765	249.8760		0.081044		0.4247	88.3622
80510.2	8.048	0.5803	251.5508		0.079776		0.4272	90.8560
80550.0	8.052	0.5804	251.5798	246.50	0.079754	0.07033	0.4273	90.8987
82781.7	8.275	0.5841	253.1814		0.078567		0.4297	93.2699
84090.0	8.406	0.5862	254.1018	248.50	0.077895	0.06895	0.4311	94.6255
85053.2	8.502	0.5878	254.7712		0.077412		0.4321	95.6073
87324.8	8.729	0.5914	256.3235		0.076306		0.4344	97.8715
87810.0	8.778	0.5921	256.6505	250.20	0.076076	0.06895	0.4349	98.3464
89596.3	8.956	0.5949	257.8411		0.075247		0.4367	100.0657
91830.0	9.180	0.5982	259.3021	251.80	0.074247	0.06757	0.4389	102.1568
91867.8	9.183	0.5983	259.3266		0.074231		0.4389	102.1917
94139.4	9.411	0.6016	260.7789		0.073255		0.4411	104.7585
95070.0	9.504	0.6030	261.3638	256.80	0.072866	0.06481	0.4419	105.7959
96410.9	9.638	0.6049	262.1966		0.072318		0.4432	107.2715
98682.4	9.865	0.6081	263.5822		0.071418		0.4453	109.7195
99090.0	9.905	0.6087	263.8275	258.50	0.071260	0.06343	0.4456	110.1516
100954.0	10.092	0.6112	264.9377		0.070551		0.4473	112.1043
103225.5	10.319	0.6143	266.2652		0.069717		0.4493	114.4295
105497.0	10.546	0.6173	267.5665		0.068912		0.4512	116.6952
107768.6	10.773	0.6202	268.8432		0.068135		0.4532	118.9041
110040.1	11.000	0.6231	270.0970		0.067384		0.4550	121.0587

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_{rw}	k_{ro}
0.050	0.0000E+00	0.1000E+01
0.082	0.9040E-03	0.9288E+00
0.115	0.4066E-02	0.8593E+00
0.147	0.9796E-02	0.7914E+00
0.180	0.1828E-01	0.7253E+00
0.212	0.2967E-01	0.6610E+00
0.245	0.4406E-01	0.5985E+00
0.277	0.6155E-01	0.5379E+00
0.310	0.8223E-01	0.4794E+00
0.342	0.1062E+00	0.4230E+00
0.375	0.1334E+00	0.3687E+00
0.407	0.1641E+00	0.3169E+00
0.440	0.1981E+00	0.2674E+00
0.472	0.2357E+00	0.2207E+00
0.505	0.2768E+00	0.1768E+00
0.538	0.3215E+00	0.1360E+00
0.570	0.3698E+00	0.9862E-01
0.603	0.4218E+00	0.6518E-01
0.635	0.4774E+00	0.3636E-01
0.668	0.5368E+00	0.1341E-01
0.700	0.6000E+00	0.0000E+00

RUN NO. 11 - SUMMARY OF COMPUTER HISTORY MATCH RESULTS

A: Displacement Parameters.

Core Length, cm	127
Cross-sectional Area sq. cm	1.3
Core diameter, cm	1.3
Porosity	0.391
Pore Volume, ml	62.92
Absolute Permeability, Darcy	4.32
Viscosity of Displacing Fluid, mPa.s	1
Viscosity of Displaced Fluid, mPa.s	375
End Point Rel. Perm. of Displaced Fluid	0.81
End Point Rel. Perm. of Displacing Fluid	0.35
Minimum Possible Saturation of Displacing Fluid	0.05
Maximum Possible Saturation of Displacing Fluid	0.7
Initial Saturation of Displacing Fluid	0.122
Injection Rate, ml/sec	0.00483
Flood Velocity, m/day	8.4
Initial Pressure Drop, MPa	5.187
c_w	4.2
c_o	0.97

B: Comparison of Experimental and Calculated Values of Pressure Drop and Recovery

time (s)	pv (inj)	recovery (frac)	recovery (cc)	recovery (data)	delta-p (mpa)	delta-p (data)	saturation (inj-pv)	wor
0.0	0.000	0.0000	0.0000		5.187253		0.1220	0.0000
300.0	0.023	0.0394	1.4332	0.20	4.757615	1.41341	0.1448	0.0175
900.0	0.069	0.1182	4.2996	0.50	3.898337	1.68920	0.1903	0.0175
1860.0	0.143	0.2444	8.8859	3.90	2.523493	2.03394	0.2632	0.0175
2700.0	0.207	0.3547	12.8989	6.30	1.320504	2.13736	0.3270	0.0175
2748.6	0.211	0.3611	13.1312		1.250847		0.3307	2.2212
3720.0	0.286	0.3953	14.3742	13.10	0.965103	1.68920	0.3505	3.5484
5100.0	0.392	0.4302	15.6431	14.60	0.747103	0.64810	0.3706	5.2995
5676.5	0.436	0.4420	16.0733		0.686494		0.3775	6.0077
6420.0	0.493	0.4556	16.5691	16.50	0.623593	0.44816	0.3854	6.9066
8604.3	0.661	0.4883	17.7588		0.498192		0.4043	9.4837
9000.0	0.691	0.4934	17.9431	17.50	0.481532	0.35852	0.4072	9.9430
11400.0	0.875	0.5203	18.9205	19.40	0.403375	0.31716	0.4227	12.6925
11532.2	0.885	0.5216	18.9686		0.399934		0.4235	12.8416
14460.1	1.110	0.5478	19.9198		0.338465		0.4386	16.1341
14580.0	1.119	0.5487	19.9548	20.40	0.336423	0.26889	0.4392	16.2675
17387.9	1.335	0.5694	20.7067		0.295917		0.4511	19.3830
19200.0	1.474	0.5812	21.1343	21.10	0.275459	0.22753	0.4579	21.3796
20315.8	1.560	0.5879	21.3794		0.264489		0.4618	22.6033
23040.0	1.769	0.6030	21.9290	21.50	0.241708	0.21374	0.4705	25.5847
23243.6	1.784	0.6041	21.9676		0.240197		0.4712	25.8065
26171.5	2.009	0.6185	22.4908		0.220780		0.4795	28.9957
26820.0	2.059	0.6215	22.5993	21.90	0.216989	0.19995	0.4812	29.7016
29099.3	2.234	0.6314	22.9622		0.204855		0.4870	32.1806
29220.0	2.243	0.6319	22.9807	22.20	0.204259	0.18616	0.4873	32.3109
32027.2	2.459	0.6432	23.3914		0.191523		0.4938	35.3586
34955.0	2.683	0.6541	23.7855		0.180175		0.5001	38.5383
37882.9	2.908	0.6641	24.1498		0.170382		0.5058	41.7210
40810.7	3.133	0.6734	24.4887		0.161832		0.5112	44.9032
43080.0	3.307	0.6802	24.7356	25.20	0.155913	0.16547	0.5152	47.4769
43738.6	3.358	0.6821	24.8049		0.154297		0.5163	48.1977
46666.5	3.583	0.6903	25.1019		0.147595		0.5210	51.3127
49594.3	3.807	0.6980	25.3816		0.141591		0.5254	54.6111
52522.2	4.032	0.7052	25.6461		0.136175		0.5296	57.7100
55450.0	4.257	0.7121	25.8969		0.131262		0.5336	61.0590
58377.9	4.482	0.7187	26.1353		0.126782		0.5374	64.2345
61305.7	4.706	0.7249	26.3627		0.122676		0.5410	67.5179
64233.6	4.931	0.7309	26.5797		0.118899		0.5445	70.8067
67161.4	5.156	0.7366	26.7875		0.115410		0.5478	73.9445
70089.3	5.381	0.7421	26.9867		0.112176		0.5509	77.3689
73017.1	5.606	0.7474	27.1779		0.109170		0.5540	80.6636
75945.0	5.830	0.7524	27.3620		0.106365		0.5569	83.8414
78872.8	6.055	0.7573	27.5392		0.103742		0.5597	87.3169
81800.7	6.280	0.7620	27.7100		0.101284		0.5624	90.6723
83700.0	6.426	0.7650	27.8177	28.00	0.099770	0.13100	0.5641	92.7861
84728.5	6.505	0.7665	27.8750		0.098974		0.5651	93.9109

87656.4	6.729	0.7709	28.0346		0.096798		0.5676	97.3655
90584.2	6.954	0.7752	28.1889		0.094745		0.5700	100.8239
91800.0	7.047	0.7769	28.2515	28.20	0.093927	0.09308	0.5710	102.2298
93512.1	7.179	0.7793	28.3383		0.092805		0.5724	104.1791
95700.0	7.347	0.7823	28.4471	28.30	0.091422	0.08963	0.5741	106.6201
96440.0	7.404	0.7833	28.4833		0.090967		0.5747	107.4710
99367.8	7.628	0.7871	28.6240		0.089223		0.5770	111.0700
102295.7	7.853	0.7909	28.7605		0.087566		0.5791	114.5758
102660.0	7.881	0.7913	28.7772	28.40	0.087366	0.08825	0.5794	115.0058
105223.5	8.078	0.7945	28.8932		0.085990		0.5812	117.9907
108151.4	8.303	0.7981	29.0223		0.084488		0.5833	121.3248
109080.0	8.374	0.7992	29.0625	28.60	0.084026	0.07998	0.5839	122.5026
111079.2	8.528	0.8015	29.1480		0.083055		0.5853	125.0109
114007.1	8.752	0.8049	29.2703		0.081686		0.5872	128.6149
115500.0	8.867	0.8066	29.3314	29.20	0.081011	0.07998	0.5882	130.4211
116934.9	8.977	0.8082	29.3894		0.080377		0.5891	132.1388
119862.8	9.202	0.8114	29.5056		0.079123		0.5910	135.5834
122790.6	9.427	0.8145	29.6191		0.077921		0.5928	139.1758
125718.5	9.651	0.8175	29.7297		0.076769		0.5945	142.9215
128646.3	9.876	0.8205	29.8377		0.075662		0.5963	146.5958
131574.2	10.101	0.8234	29.9433		0.074598		0.5979	150.1992
134502.0	10.326	0.8262	30.0465		0.073574		0.5996	153.7357
137429.9	10.550	0.8290	30.1475		0.072588		0.6012	157.4221
140357.7	10.775	0.8317	30.2462		0.071638		0.6027	161.2837
143285.6	11.000	0.8344	30.3428		0.070722		0.6043	165.0831

C:

CALCULATED RELATIVE PERMEABILITIES
(Relative to End Point Oil Permeability)

S_w	k_{ri}	k_{rp}
0.050	0.0000E+00	0.1000E+01
0.082	0.1473E-05	0.9515E+00
0.115	0.2707E-04	0.9029E+00
0.147	0.1486E-03	0.8542E+00
0.180	0.4974E-03	0.8054E+00
0.212	0.1270E-02	0.7565E+00
0.245	0.2730E-02	0.7076E+00
0.277	0.5216E-02	0.6585E+00
0.310	0.9138E-02	0.6093E+00
0.342	0.1499E-01	0.5600E+00
0.375	0.2333E-01	0.5106E+00
0.407	0.3481E-01	0.4610E+00
0.440	0.5016E-01	0.4112E+00
0.472	0.7020E-01	0.3613E+00
0.505	0.9583E-01	0.3111E+00
0.538	0.1280E+00	0.2607E+00
0.570	0.1679E+00	0.2100E+00
0.603	0.2166E+00	0.1588E+00
0.635	0.2753E+00	0.1072E+00
0.668	0.3455E+00	0.5473E-01
0.700	0.4286E+00	0.0000E+00